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Conceptual Design Of A Space-Based Multimegawatt MHD Power System

Task 1 Topical Report
Volume I: Technical Discussion

Prepared For

DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER
PITTSBURGH, PA 15236-0940

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LIST OF ACRONYMS

ACES	Action Commitment Expediting System
AESD	Advanced Energy Systems Division
APT	Advanced Power Train
β	Hall parameter
BAC	Boeing Aerospace Company
CD	Control Drum
CDIF	Component Development and Integration Facility
CSS	Core Structural Support System
DOD	United States Department of Defense
DOE	United States Department of Energy
EMI	Electromagnetic Interference
EML	Electromagnetic Launchers
EUT	Eindhoven University of Technology
EVA	Extra Vehicular Activity
FEL	Free Electron Lasers
HEL	High Energy Lasers
IMACS	Integrated Management and Control System
INEL	Idaho National Engineering Laboratory
IUS	Inertial Upper Stage
LANL	Los Alamos National Laboratory
MHD	Magnetohydrodynamic
MIT	Massachusetts Institute of Technology
MMW	Multimegawatt
MSE	Mountain States Energy, Inc.
NDR	NERVA Derivative Reactor
NERVA	Nuclear Engine for Rocket Vehicle Application
NPB	Neutral Particle Beam
OMV	Orbital Maneuvering Vehicle
PCS	Power Conditioning System
PETC	Pittsburgh Energy Technology Center
R&D	Research and Development

LIST OF ACRONYMS

RFP	Request for Proposal
RFQ	Request for Quote
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SPA	System Performance Analysis
STS	Space Transportation System
TIT	Tokyo Institute of Technology
WBS	Work Breakdown Structure

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1.0 INTRODUCTION

This Topical Report presents the results of Task 1 of the Feasibility Assessment for Space-Based Multimegawatt MHD Power Systems program. It consists of two volumes.

Volume I contains the results of the work performed in Task 1 as presented and discussed in Sections 2 through 6. Section 2 is an executive summary of the work. Section 3 contains a complete description of the space-based multimegawatt MHD power system conceptual design. System performance and operations characteristics are also identified. It has been assumed in Task 1 that the system provides power to a Neutral Particle Beam (NPB) Weapon, for which generic load requirements are presented. Integration of the power system and NPB with alternative space launch vehicles is also discussed in this section. Section 4 contains a discussion of key technical issues and questions requiring additional investigation. Section 5 presents the Research and Development plan which is proposed for Task 2. Conclusions and Recommendations are contained in Section 6.

Volume II of the report contains the System Requirements, Design Guidelines and Assumptions for the space-based multimegawatt MHD power system. This is an initial system specification document which will be refined during the course of Task 2.

Topical report WAESD-TR-88-0004 provides supplemental information in the following areas: design and performance, cost, spacecraft integration, power conditioning, and subsystem/component development and testing. The effort expended in preparing the information in the supplemental report and this report itself was performed using AES discretionary funds.

2.0 EXECUTIVE SUMMARY

A specific space-based MHD power system and its component elements have been identified and described, a conceptual design has been prepared, technical uncertainties associated with the system have been specified, and plans to resolve these uncertainties have been developed under Task 1 of this program.

Power System Requirements and Design Guidelines (Volume II of this report) were prepared based upon existing and evolving documents and specifications for SDI burst power requirements. A generic Neutral Particle Beam (NPB) space platform was considered in establishing representative requirements for the space-based multimegawatt MHD power system.

The conceptual disk MHD generator space power system has a specific power double that of conventional MHD generators (~ 20 MJ/kg) with hydrogen heated to a temperature of 2900 K. Because of hydrogen's high specific heat, hydrogen-driven systems can be expected to reach specific powers which are an order of magnitude greater than for combustion-driven systems.

The heat source is a solid core nuclear reactor of the type developed and demonstrated in the NERVA/Rover Program, which heats hydrogen to delivery temperatures of approximately 3000 K at pressures of 17 atmospheres with composite (UC-ZrC-C) fuel elements.

Open cycle space power systems exhaust to space, therefore, very high pressure ratios are available. However, the disk MHD generator allows both high conversion efficiency and a compact system with moderate pressure ratios.

The nonequilibrium disk MHD generator uses a simple solenoid magnet configuration and few electrodes. This generator requires minimum power conditioning and has high power density when driven by hydrogen seeded with a very small (0.5×10^{-4} mole fraction) concentration of cesium. The combination of a nuclear reactor with the disk MHD generator operating in the nonequilibrium regime produces a net power of 100 MW_e with a mass flow of 5.5 kg/s of hydrogen. The system has very high energy extraction, in the order of 20 MJ/Kg. As a result, the launch requirement is minimal.

The system is designed to provide 100 MW_e of conditioned DC power to the load over a total accumulated time of 500 s. It meets the duty cycle requirements for commissioning, periodic test operation and mission power burst. Alternative methods for control and operation have been investigated and are available. System response time is the principal criterion in selection of control method.

The hardware elements of the system are configured in an axially oriented arrangement. The volume envelope of the system is within the cargo carrying capability of the space shuttle, and can be launched together with an Orbital Maneuvering Vehicle (OMV) if required for final orbital assembly. Likewise, the system is capable of being launched by existing unmanned vehicles. The estimated liftoff mass of the system dry is 7330 kg; including hydrogen inventory it is 13,600 kg excluding the power conditioning.

Key technical issues have been addressed in planning for Task 2 of the program. These relate principally to further investigation of the disk MHD generator and plasma for the operational condition of the system and mission.

Even though a substantial base exists for inert gas systems, hydrogen plasma properties have not been demonstrated. Experiments to verify plasma properties and stable performance of cesium seeded hydrogen plasma at the operating conditions chosen for the concept are essential. Likewise, experiments to confirm predicted high fractional energy extraction from discrete radial zones of the disk generator are essential for verification of the technical viability of the system.

The small molar fraction of cesium in the hydrogen reactor coolant will not impact thermal/fluid characteristics of the reactor; further, no problem is found in compatibility for life requirements of the fuel element. Electrical effects are engineering issues. Otherwise, the nuclear reactor design is based on similar reactors that are in advanced development including completed test operation. Thus, there are no key technical issues identified for the reactor, and work in Task 2 will be limited to refinement of the design for the specific mission application.

A Research and Development Plan is included in Section 5 of this report which proposes a Task 2 scope of work addressing the key technical issues identified. The proposed plan encompasses the conduct of 2 major experiments for definition of plasma and disk generator performance at the conditions required for the conceptual design. The experimental program is presented including test facilities, parameters, and data to be collected. Estimated cost and schedule including task milestones are provided. These experiments are essential to confirmation of the technical viability of the Power System.

In addition, ongoing work is proposed during Task 2 in systems analysis and integration, materials investigations, and refinement of subsystem conceptual designs.

The schedule for the proposed disk generator experiment dictates that timely decisions are made concerning selection of the test site, test equipment procurement, and test article design and fabrication.

The results of Task 2 implementation are expected to confirm the viability of the system concept for the SDI mission.

It is concluded that the Space-Based Multimegawatt MHD power System is a feasible concept having performance potential that is superior to other potential solutions for the defined application.

3.0 SYSTEM DESIGN

Both functional requirements and design objectives have been established for the MHD Power System. This section summarizes the requirements and objectives for Task 1 of the Feasibility Assessment for Space-Based Multimegawatt MHD Power Systems. Task 1 consists of the conceptual design of the MHD power system and the preparation of a development plan for Task 2. The initial set of functional requirements and design objectives have been used to guide the Task 1 conceptual design effort. More detailed design and interface requirements will be developed as the system design evolves through subsequent program tasks. In addition, the system designer must be cognizant of the development of more comprehensive design and interface requirements in order to understand the technical issues and develop a responsive conceptual design. For this reason, a detailed package of system requirements, design guidelines, and interface requirements has been prepared and included as Volume II of this Task 1 topical report. The Volume II requirements document is incomplete at this stage of the system design due to the limited scope of the Task 1 effort. It has been prepared as a separate document to facilitate updating of the contents and its use by all project participants in subsequent program tasks.

The functional requirements used as input to the Task 1 conceptual design effort are the following:

Application: A space-based MHD burst power system integrated with a space platform to power a weapons system. For study purposes, a tube-type Neutral Particle Beam (NPB) weapon that requires semi-annual testing has been selected to assess the MHD power system. The generic load requirements for this application are presented in Figure 3-1.

Burst Power: A burst power level of 100 MW_e for at least 500 s (50,000 MJ) is required.

Load voltage requirements: 100 kV

Number of tests: 20 cycles (startup/shutdown)

Test duration: Approximately 7 s

Test power level: 100 MW_e (A 2 to 3 s initial power level of 25 MW_e prior to the final 4 to 5 s of full power is desirable.)

Full power level: 100 MW_e (for 500 s, including tests)

Figure 3-1. Generic Load Requirements

Power Conditioning: The power system output of 100 MW_e shall be conditioned and delivered to a dedicated NPB weapon system electrical buss at a direct current load voltage of 100 kV as specified in Figure 3-1.

Duty Cycle: The duty cycle includes initial startup, semi-annual testing at full burst power (20 cycles of 4 to 5 s each), and full power battle burst mode operation assumed for an additional 400 s. The duty cycle and load profile shall be as defined in Figure 3-2 and Figure 3-3.

Working Fluid Inventory: A dedicated working fluid inventory (tankage for cryogenic hydrogen and cesium seed) sufficient for a full 10 year lifetime duty cycle plus tank ullage, system cooldown, and estimated losses is required.

System Lifetime: The power system shall be designed for a lifetime of 10 years.

External Power: The MHD power system shall be self-sufficient when operating in the ready and burst operating modes. External power for the standby mode (~ 30 kW_e) shall be supplied to the MHD power system from a solar or SP-100 nuclear powered subsystem incorporated in the space platform. All reactor safety control and instrumentation power shall be supplied by an independent, uninterruptible power source, such as an electrochemical battery, that is incorporated in the MHD power system and continuously recharged during standby and dormant periods.

The power system design objectives are as follows:

- High reliability, because of the strategic importance of the SDI mission and the need for extended periods of operation or parking without access for maintenance or inspection

- Rapid responsiveness, covering rapid ramp-up to power and quick flexibility to variations in power demands

OPERATING MODE OR TRANSITION	OPERATING TIME	MMW POWER SYSTEM POWER OUTPUT	MMW POWER SYSTEM POWER DEMAND[1]	TRANSIENT TIME ALLOWED
Standby (or Station Keeping)	Continuous	0	30 kW_e (Average) 50 kW_e (Peak)	-
Standby to Ready Mode	-	0-25 MW_e	-	< 90 s
Ready	2-3 s	25 MW_e	-	-
Ready to Burst Mode	-	25-100 MW_e	-	< 1 s
Burst Mode[2] (Test/Semi-annual)	4-5 s	100 MW_e	-	~ 100 s[3]
Burst Mode	$\leq$ 400 s	100 MW_e	-	-

Notes: (1) Standby power demand shall be supplied by a solar or SP-100 nuclear power subsystem on-board the space platform.

(2) A semi-annual test is defined as a transition from the standby mode to the ready mode, operation at the 25 MW_e ready mode for 2-3 s, ramp up to full power (< 1 s), burst power operation for 4-5 s, then shutdown to the standby mode.

(3) Total semi-annual test duration from standby to full power to standby.

Figure 3-2. MMW Power System Duty Cycle Requirements

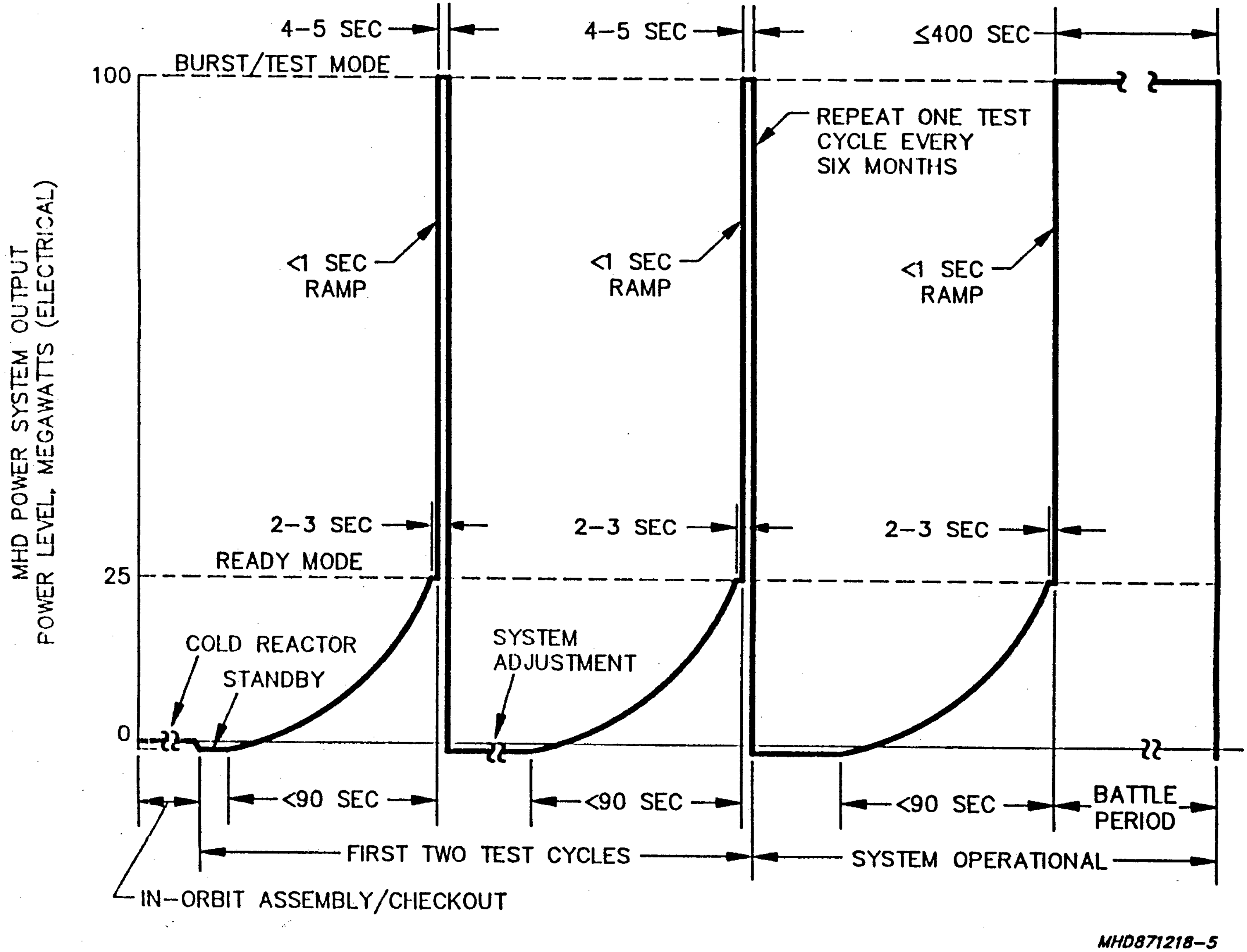


Figure 3-3. Power System Load Profile Requirements

- Adaptability to specific power conditioning needs, to meet the differing requirements of the variety of weapon devices that might be energized by the MHD power system

- Adaptability to specific space platform configurations

- Utilize on-board fuels made available from other subsystems' disposals

- Free of disturbances to space platform stability, by avoidance of such perturbations as unbalanced thrust or internal machinery dynamics

- Compliance with all applicable nuclear safety criteria

- Survivability, both as regards the space environment as well as a hostile attack environment

- Avoidance of harmful effluent effects which could damage/deteriorate/corrode materials, and interfere with command and control and weapon system/space platform operation

3.1 Description

3.1.1 Overall System

The power system designed by the Westinghouse Team is focused on MHD with thermal energy provided by a nuclear heat source. The MHD generator employs the disk concept and takes full advantage of the disk's unique capabilities in meeting the power requirements imposed by this application with a minimum volume, minimum mass system. The reactor design for the proposed power system will be taken from the NERVA/Rover Program technology. That technology, intended specifically for space application, developed extensively by the LANL, Westinghouse and others has been confirmed experimentally. Thus, its application in the proposed system is natural, and it is also expedient since the reactor's relatively advanced development state will permit primary focus on required developmental work on the MHD components.

The power system is shown schematically in Figure 3-4 and pictorially in Figure 3-5. The working fluid is hydrogen, which could be drawn either from the SDI-mission supply, or a dedicated hydrogen supply. In this study, the latter approach has been assumed, and the system concept described herein includes liquid hydrogen storage. During power operation, as indicated in Figure 3-4, hydrogen is drawn from storage and pumped sequentially through the power conditioning system, disk cooling, and reactor cooling passages before it enters the reactor for final heating. Therefore, the system utilizes a very advantageous recuperative approach that avoids the need for system heat rejection, and minimizes the thermal input required at the reactor. A small additional flow of hydrogen is directed to the magnet to provide low temperature cooling.

Upon the hydrogen completing its cooling function, cesium seed is added which flows through the reactor to the MHD generator. The system is once-through and employs no seed recovery feature.

The seeded hydrogen exits the generator in two opposing, balanced jets. In this way, thrusts are essentially cancelled, and the effluent stream leaving the system is localized and directed away to minimize mission interference. The spent magnet-cooling hydrogen is mixed with the effluent in the discharge nozzle. Control of this low temperature flow permits active fluidic control of the discharge nozzle thrust reactor, insuring thrust cancellation.

The MHD disk generator is a Hall-effect device. Thus, operation with high Hall fields (greater than 10 kV/m) is both intentional and beneficial. In fact, it is most beneficial in this particular application, where system size and mass are of crucial concern, because it assists in achieving high

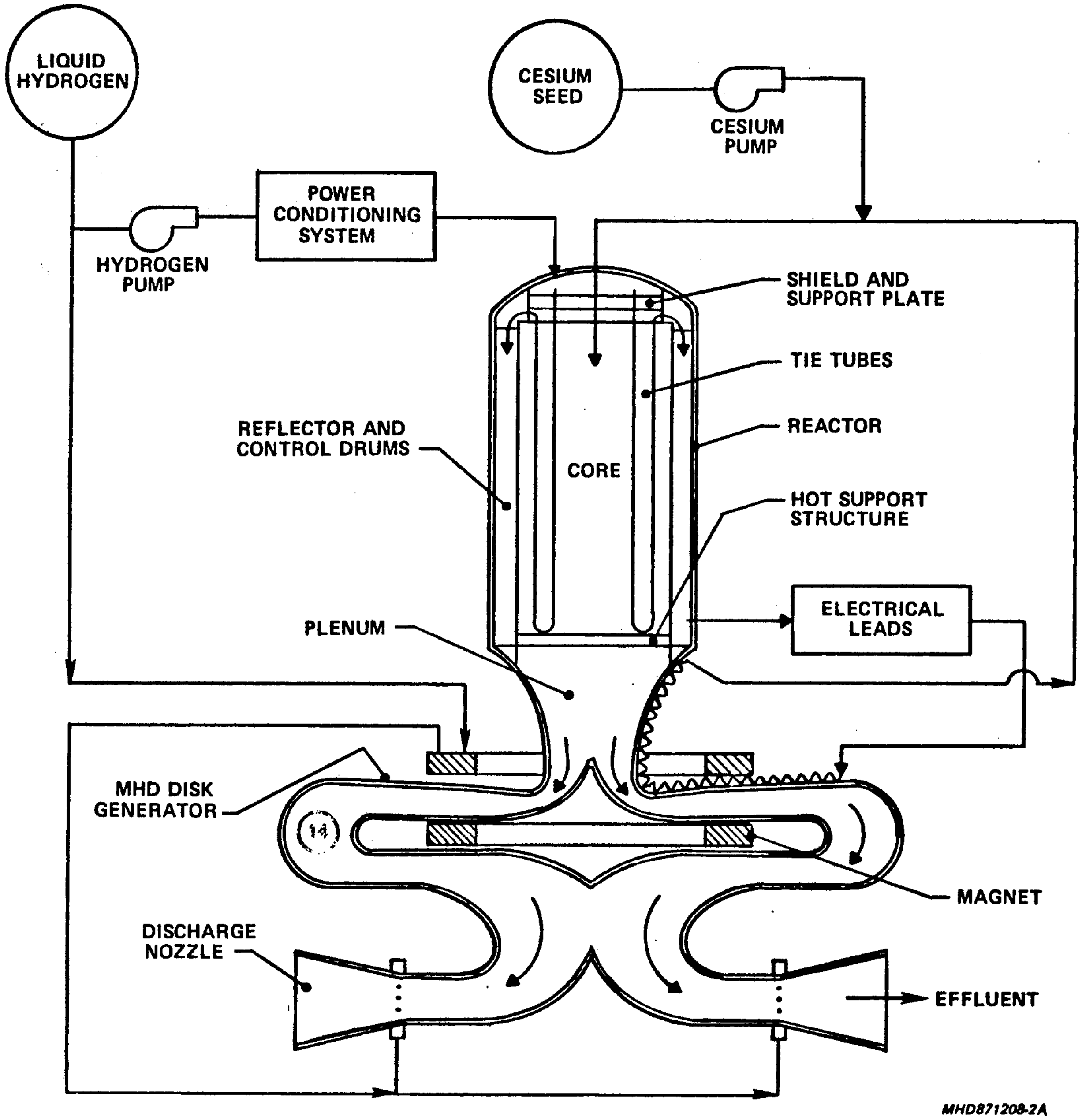


Figure 3-4. Power System Schematic

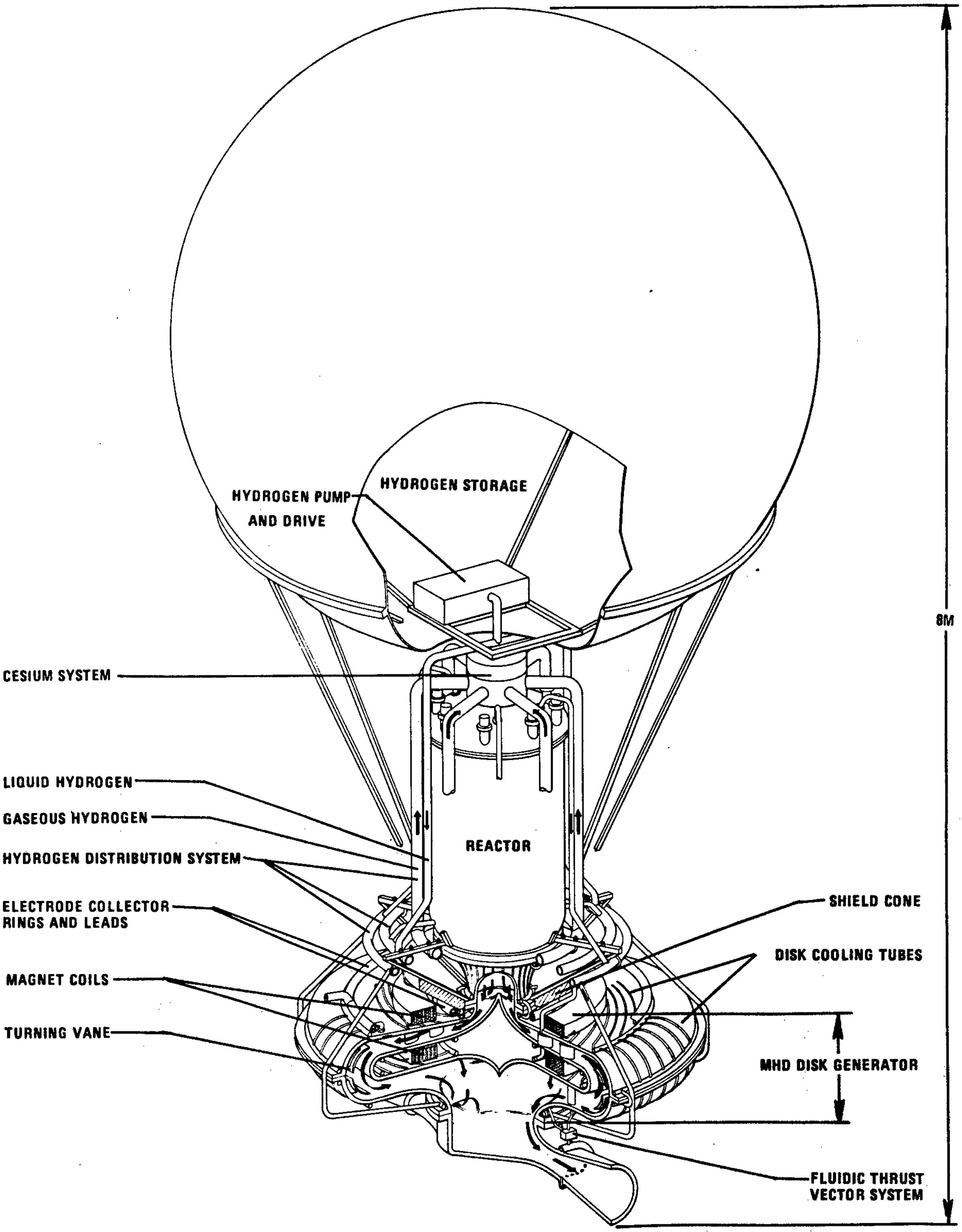


Figure 3-5. MHD Power System Concept

power densities relative to those that can be obtained in the more conventional, Hall field-limited (less than 4 kV/m) linear MHD channels. Typically, linear channel power densities will fall in the vicinity of 10 MW/m^3 of active volume, and 2 MJ/kg of working fluid, corresponding to enthalpy extractions in the 10% to 20% range. The disk generator, however, due to the high Hall field, nonequilibrium ionization, and the enhanced conductivity it promotes, is capable of increasing appreciably the value of these parameters. In the present design, the predicted mean power density exceeds approximately 7500 MW/m^3, with 20 MJ/kg extracted from the hydrogen flow.

The proposed MHD generator employs a two-disk design. Upon entering the generator from the top, the seeded hydrogen flows radially outward in the first disk, expanding and producing power. It then reverses its direction, entering the second disk, to make a radially-inward pass. In the present generator concept, all predicted power production occurs in the first disk. The generator employs a double-solenoid, separately-excited magnet. In this concept, the required field strength is 4 Tesla at the magnet axis. The double solenoid feature is used to properly tailor the B-field at the first disk where maximum power production will occur. The aluminum solenoid cores are cryogenically cooled with hydrogen. The design of the disk generator is discussed in more detail in Section 3.1.5.

Statepoint predictions are discussed in Section 3.2. In the proposed system, the required net power output from the MHD generator system, 100 MW_e, is produced with a hydrogen flow rate of 5.53 kg/s. As Figure 3-4 indicates, the full flow rate is used first to cool the power conditioning system and certain reactor internals, then to cool the power leads, and finally the generator walls and the reactor exit plenum. An external hydrogen stream of 0.078 kg/s is provided to absorb the 35 kW magnet cooling load. The estimated generator cooling load is approximately 3.6 MW, with another 2.9 MW in the reactor plenum. Before exiting the generator cooling system, all hydrogen is vaporized and enters the reactor after receiving seed at approximately 650 K. The design seed concentration is 5×10^{-5} mole fraction, (approximately 0.3 wt-%) corresponding to a cesium flow rate under full power conditions of 0.018 kg/s. At the reactor exit, the design values of stagnation temperature and pressure are 2900 K and 17 atm, respectively.

The generator is sized to produce the required net power output at the load of 100 MW_e, including conversion and transmission losses.

The generator is divided into three sections electrically, with approximately 7000 amps load current in the entrance and exit sections (10,000 amps drawn in the center section) with a 12,000 V potential. Thirty two percent of the power is extracted in the first (initial section) load portion of the generator, 51% in the central portion, and 17% in the exit portion, beyond the magnet radius. During operation, the hydrogen and cesium pumps are driven electrically from the power produced by the generator. At full field, the stored energy in the magnet is 6.5 MJ, requiring 35 kW for continued operation. The required initial magnet charging energy and operating power is readily supplied by an onboard battery system, as is the energy required to bring the hydrogen pump up to speed and to power the cesium pump. The use of batteries to provide the total energy requirements for the magnet avoids the switching difficulties and associated reliability problem(s) involved with a "bootstrap" startup and two-level power operation. In addition, this scheme eliminates the need to provide a high current/low voltage conversion circuit in the power conditioning system.

During standby, approximately 23 kW_e is required from the platform power supply to maintain readiness. About 50 W of this is required to operate the cesium heater. The remainder of this drives a refrigeration system to maintain the magnet at its operating temperature and to cool the hydrogen tankage to prevent boil off. Heat rejection from this system will require the inclusion of an 18 m^2 radiator operating at 400 K.

As already indicated, a major advantage of the MHD disk generator concept in this particular application concerns its ability to achieve high power densities on both a volumetric basis and a working fluid mass basis. Thus, application of the disk concept inherently leads to small, low-mass power systems with significant improvement possible with power scaleup. The estimated masses of the major system components, exclusive of power conditioning equipment, are as follows:

	Mass (kg)
Reactor & Internal Shielding	2,200
Shielding (Magnet & Electronics)	700
Liquid Hydrogen (initial mass), Container, & Insulation	6,260
Magnet	720
MHD Generator	2,460
Seed (initial mass), Container, & Pump	40
Associated Piping, Structure, Misc. Components	1,220
Total (exclusive of power conditioning)	13,600

While these masses are attractive, further refinement of the design will be achieved during Phase II. This will be done analytically by varying such parameters as the magnetic field strength, the MHD generator inlet pressure, seed concentration, the hydrogen flow rate, and the generator inlet Mach number. The Westinghouse-developed System Performance Analysis (SPA) computer program will be applied in this work. SPA is a general system analysis code that can be applied in predicting the size and mass of power system components in addition to calculating thermal performance. The code is well suited for parametric, system optimization studies required by this project and has been successfully applied previously.

The power system is also compact. The component arrangement depicted in Figure 3-5, including the liquid hydrogen tank, can be enclosed by a cylindrical envelope measuring 4.3 m (dia.) x 8 m. This envelope does not include the power conditioner, whose mass and weight implications are subject to judgments based on existing ground-based equipment, design studies for large photovoltaic space systems, and predicted success with miniaturization. The current estimate for the power conditioner is based on

0.253 kg/kW$_e$ projected for this application. The bulk of the power conditioning gear is not highlighted as a technical issue unique to this power system or addressed specifically in this study due to the focus on power conversion system feasibility. This technology is a technical challenge for all high powered space-based SDI platform concepts. This is a generic development issue that must be solved by a concurrent program which serves the SDIO mission as a whole.

Operationally, the nuclear/MHD power system offers significant flexibility for power control. For full power and quarter power operation, full hydrogen flow will be supplied to the reactor and system, and the power conditioning system will provide the primary control. The seed flow to the generator will be adjusted to provide optimum performance of the generator. For quarter power operation, which takes place for short periods, full flow of seed and hydrogen will be supplied to the generator, and the center and exit sections of the generator will be shorted out by the power conditioning system. This arrangement permits an extremely rapid transition between quarter power and full power, limited only by the response time of the Power Conditioning System and the transit time of the gas through the generator.

Alternative control options include varying the mass flow through the generator, varying the reactor temperature, and varying the magnetic field. All three of these options provide sluggish response at best. The fastest of these is varying the mass flow, which is limited by the response rate of the hydrogen flow control valve and/or the response of the hydrogen pump. The thermal time constant of the reactor is large, relative to the desired control response. The large amount of energy stored in the magnet also makes it unsuitable as a control element. Varying the seed flow as a control element is limited by the seed pump response time and by the transport lag through the reactor and generator. With the small seed flow required, the response time of the seed flow controls can be made quite fast. The transit time through the reactor upper and lower plena is the limiting factor on the seed transit, and can be roughly estimated to be in the order of 100 ms. Active control of the seed flow rate is therefore a viable mechanism for insuring that the generator operates at its optimum level.

The open-cycle system effluent is a mixture of only hydrogen gas and cesium vapor. Thus, the number of effluent constituents is held to a minimum, and, most important, due ultimately to the disk generator's unique ability to operate with a high level of nonequilibrium ionization, both the seed concentration and the working fluid mass flow rate requirements also are minimized. In addition, hydrogen is the same effluent that will be produced by the SDIO mission system and is relatively innocuous. Most of the cesium, as indicated above, could be recovered if necessary. Therefore, the environmental impact produced by the nuclear/disk generator power system is inherently small in the open-cycle mode, and could be reduced even further by incorporating appropriate auxiliary system design features.

Figure 3-6 shows the gross heat balance for the system at full power operation. Of the energy supplied to the plasma, 261 MW_t comes directly from the reactor. The remainder comes from regenerative cooling of the system components and the hydrogen pump power. A total of 108 MW_e is generated by the disk generator and 161 MW_t is rejected in the effluent stream.

In standby, the system requires 23 kW_e of power from the platform (Figure 3-7). Of this, nearly all is used to drive the cryogenic refrigeration equipment which cools the magnet and the hydrogen storage tank. With a sink temperature of 400 K at the radiator and a cryogenic temperature of 20 K, somewhat more than 22 kW of the total 23 kW input energy is radiated to space from the cooler. The remaining power, about 0.35 kW, is used to charge the battery system, maintain the cesium seed at temperature, and to operate controls and communication systems.

3.1.2 Reactor Heat Source and Shielding

The developed technology of the demonstrated NERVA derivative (NDR) nuclear reactor illustrated in Figure 3-8 is selected for the hydrogen plasma heat source. The reactor to be used as the basis for this program is the small nuclear rocket engine reactor.[(3-1)(3-2)] The reactor engineering, nuclear

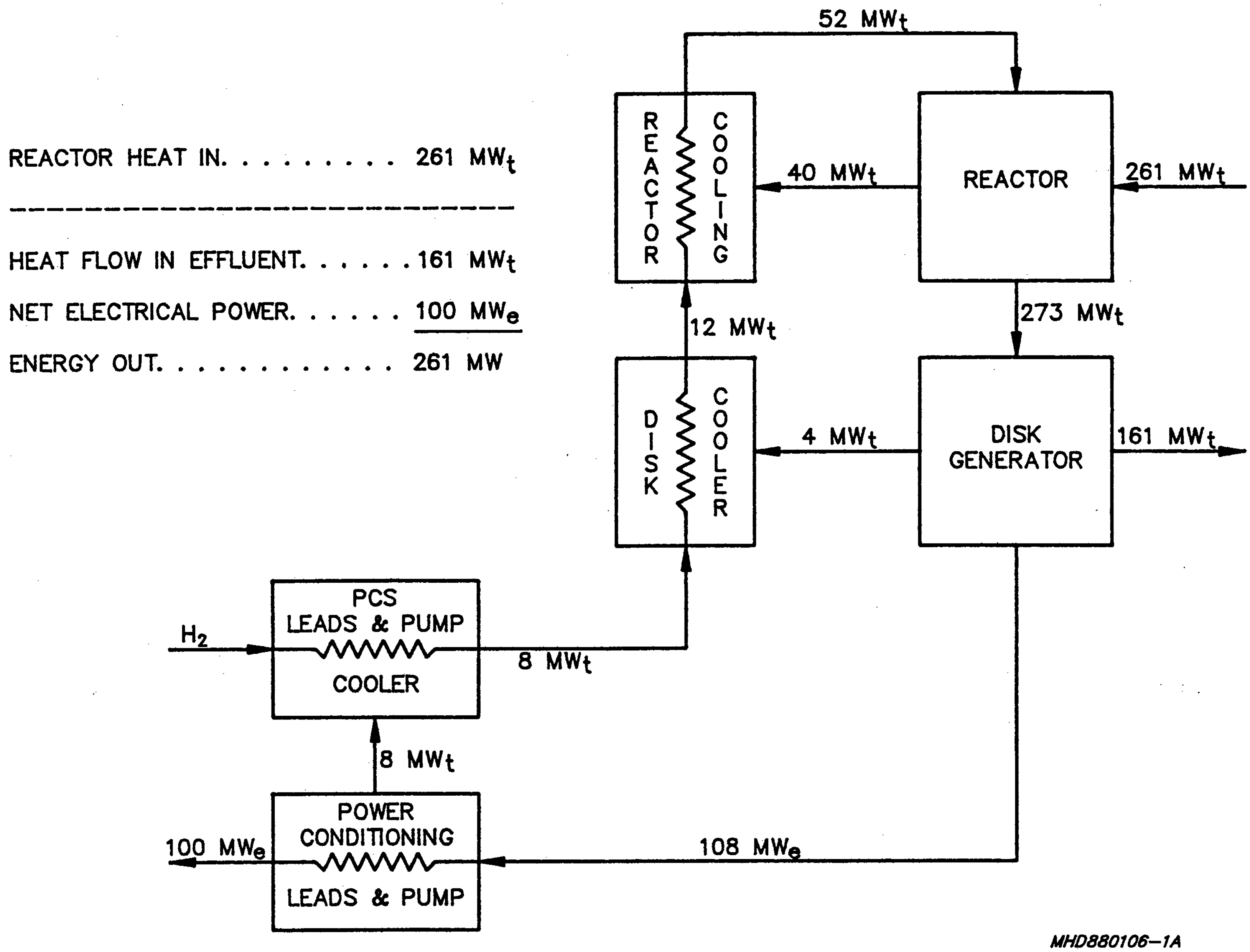


Figure 3-6. Burst Power Operation Heat Balance

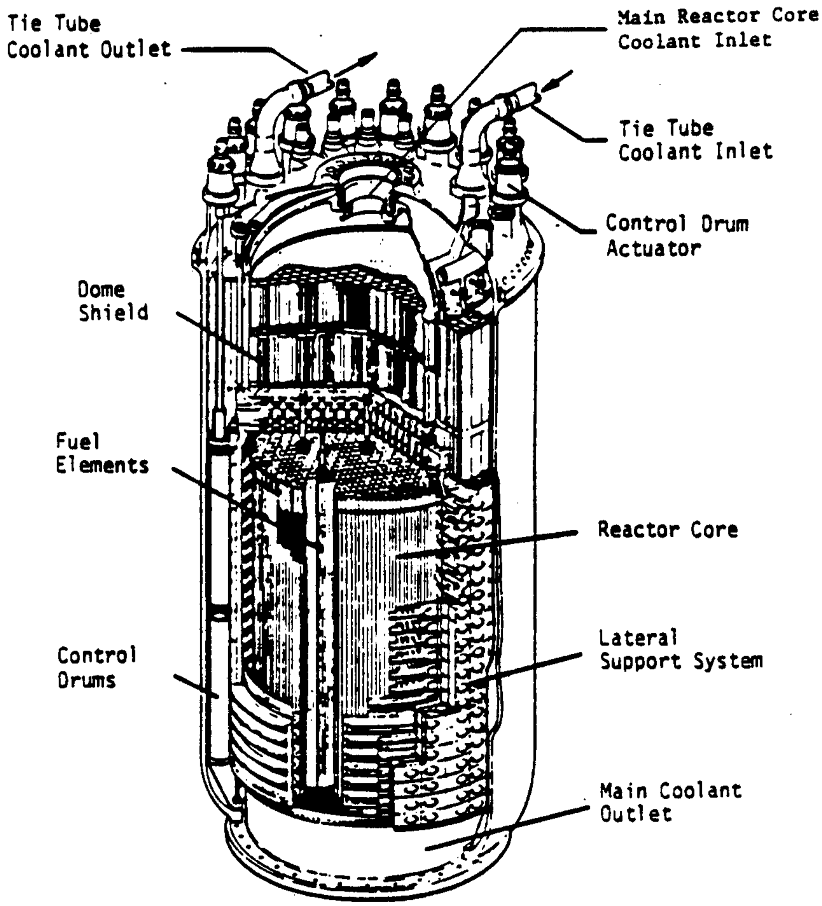
Heat Input

Electrical Power from Platform	23 kW_e

Heat Extraction

Power to Cesium Heater	0.05 kW_t
Power to Battery Charging	0.10 kW_t
Hydrogen Storage Cooling	0.11 kW_t
Magnet Cooling	0.12 kW_t
Communication and Control	0.20 kW_t
Heat Rejected from Cryogenic Refrigeration	22 kW_t
	23 kW_t

Figure 3-7. Standby Operation Heat Balance



- Epithermal, Graphite-Moderated Hydrogen-Cooled Reactor
- Enriched (93%) Uranium-235 Fuel
- Power Flattening By Varying Fuel Loading and Flow Distribution
- Core Inlet Orifices Control Flow Distribution
- Core Supported By Cold-End Support Plate and Structural Tube Arrangement
- Reactivity Control By Rotating Drums in Reflector

Figure 3-8. Illustration of NERVA Derivative Reactor subsystem technology and design were demonstrated in 20 reactor tests with power levels up to more than 4,000 MW. The basic function of the nuclear reactor heat source is to provide sensible heat to the hydrogen coolant as a simple heat exchanger. The NDR nuclear reactor was chosen as the heat source over chemical systems and other nuclear reactor types for the following reasons:

- As compared with chemical heat sources, the initial reactor system mass at lift off (heat source equipment plus consumables, < 7500 kg) is much less than any known chemically-fired system.

- The reactor is fully controllable over its range of power capability; response to power demands, namely, startup, shutdown, and changes in power level, is rapid; and there are no penalties from cyclic operation. Chemical systems are typically less amenable to such flexible operational maneuvering and precise trimming.

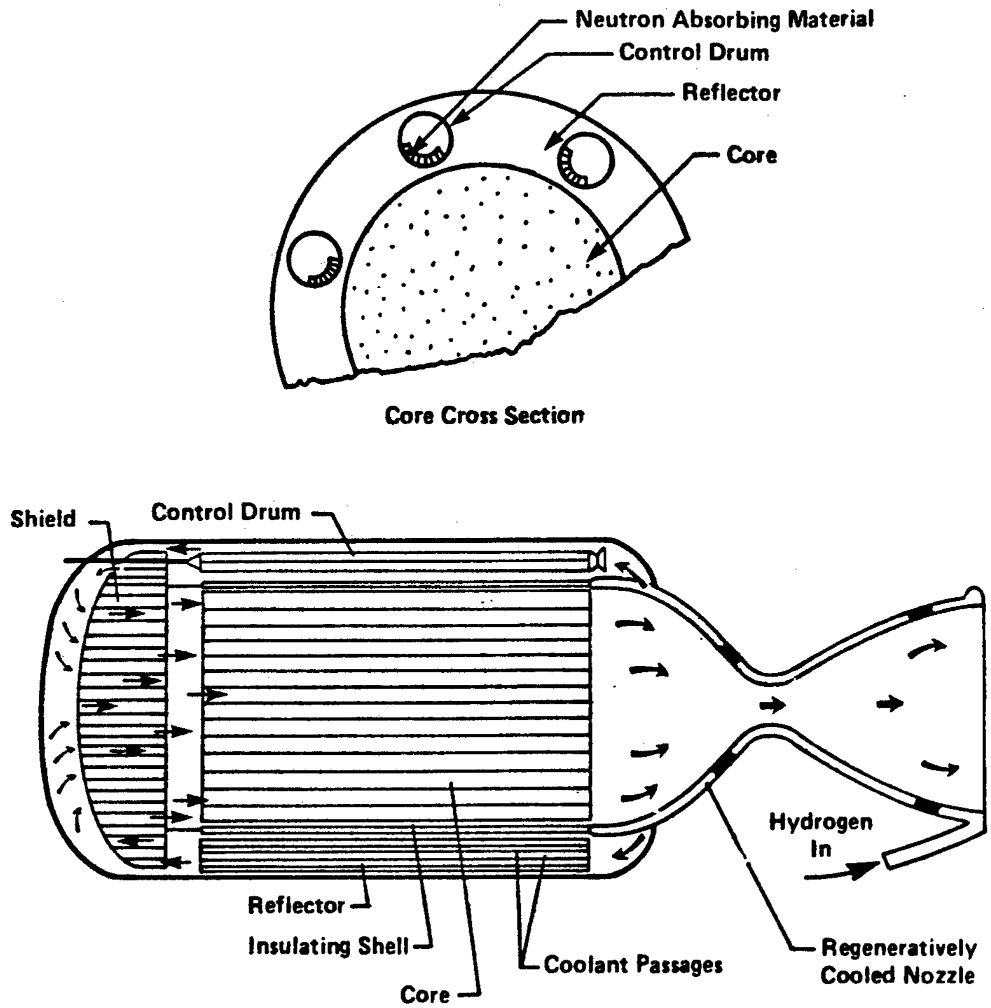
- The nuclear reactor provides heating without combustion. The hydrogen with low cesium seed is probably the most benign effluent possible for this application, significantly more desirable than the products of combustion.

- Compared to other candidate nuclear heat sources, a gas-cooled nuclear system allows a higher exit temperature (3000 K vs < 1300 K) than liquid cooled and has lower mass. The NERVA derivative (solid core) gas-cooled reactor was selected over other gas-cooled concepts, such as the particle bed and gaseous core, because these alternate concepts are one to two generations behind the maturity level of the NERVA derivative technology.

Nuclear subsystem technology issues/development efforts associated with the selected technology are addressed in other programs and not treated within the scope of this effort. The technology currently available has been identified for use in defining the system concept described herein.

A schematic of the NERVA derivative reactor is shown in Figure 3-9. The source of heat is the energy generated by the fission events in the fuel elements which make up the reactor core. In the NERVA derivative reactor, the fuel elements are composite graphite matrix elements dispersed with fissionable material and extruded with 19 axial passages for the hydrogen coolant. The reactor core is surrounded by a reflector of a moderating material, beryllium, and sized to "reflect" escaping neutrons back into the core to maintain the chain fission reaction. Active control of the fission rate is accomplished by control drums, rotatable drums in the reflector with neutron absorbing material covering part of their circumference. Rotating the neutron absorbing material, or poison, inward toward the reactor core prevents neutrons from augmenting the chain reaction. Passive control of the fission rate is achieved by the design having a negative temperature coefficient, that is, a reduction in coolant temperature, and therefore reactor temperature, produces additional moderation of neutron energy levels leading to a higher population of fission causing neutrons in the core; an increase in temperature reduces moderation and more neutrons are lost or absorbed without contributing to fissioning. The negative temperature coefficient of reactivity results in stable operation with almost no control drum motion required to maintain temperature. More control drum motion is required to accomplish power trimming or transients such as startup and shutdown. Continuous monitoring of the temperature, fission event rate (as deduced from radiation levels), and power are provided both for normal control purposes as well as safe shutdown to subcritical conditions (no chain reaction) if off normal conditions develop.

In operation, the liquid hydrogen is routed through the structures needing to be cooled and warmed in a recuperative manner before being introduced to the fueled elements of the core. In the present system, which utilizes the reactor as a source of hot working fluid to the MHD generator, cesium is injected into the hydrogen stream before it enters the reactor inlet plenum. After passing through the hot reactor and removing the nuclear generated heat, the coolant exits at desired pressure and temperature as a clean hydrogen stream seeded with cesium. The exhausted gas mixture then



Note: Nozzle and reflector flow path differs in MHD power system application,
Principles of reactor operation are the same.

Figure 3-9. Schematic of NERVA Reactor as Field Tested (Program of 20 Reactor Tests) flows through the nozzle where excess pressure and temperature are converted to the desired kinetic energy for introduction into the disk generator.

The nuclear reactor technology and nuclear system design is based on a scaled down version of NERVA NR-1 and the advanced Pewee reactors.[3-2] All key features of this design, and their associated technologies, have been demonstrated successfully in reactor tests during the NERVA/Rover Program. This includes reactor control, core support system, hot-end support composite materials, regeneratively cooled metal core support elements (tie tubes), and fuel-element exit-gas thermocouples.

The reactor and components have been designed and experimentally demonstrated, including the dynamic loads and conditions experienced in launch operation.

The NDR concept incorporates composite fuel elements, graphite moderated epithermal core with demonstrated control characteristics, that are thermally stable, responsive, and compatible with the system requirements and power conversion system. The nuclear system is illustrated in Figures 3-10 and 3-4.

In addition to overall performance goals, identified in the System Design, Section 3.0, the reactor must meet specified general safety criteria. The core concept has demonstrated a negative power coefficient to assure stability. It also must remain subcritical in all accident conditions including immersion in water or core compaction resulting from accidents during transport or launch. Two independent shutdown systems are also being included to assure safe shutdown from all operational states.

The tie tube core support system provides NDRs with two independent means for heat removal. In the event the reactor is shutdown due to loss of flow or loss of coolant, hydrogen is used to remove any decay heat through the normal flow path under this emergency condition. In the event that the normal flow path cannot be utilized, the tie tube support system provides the secondary heat removal system to remove any decay heat.

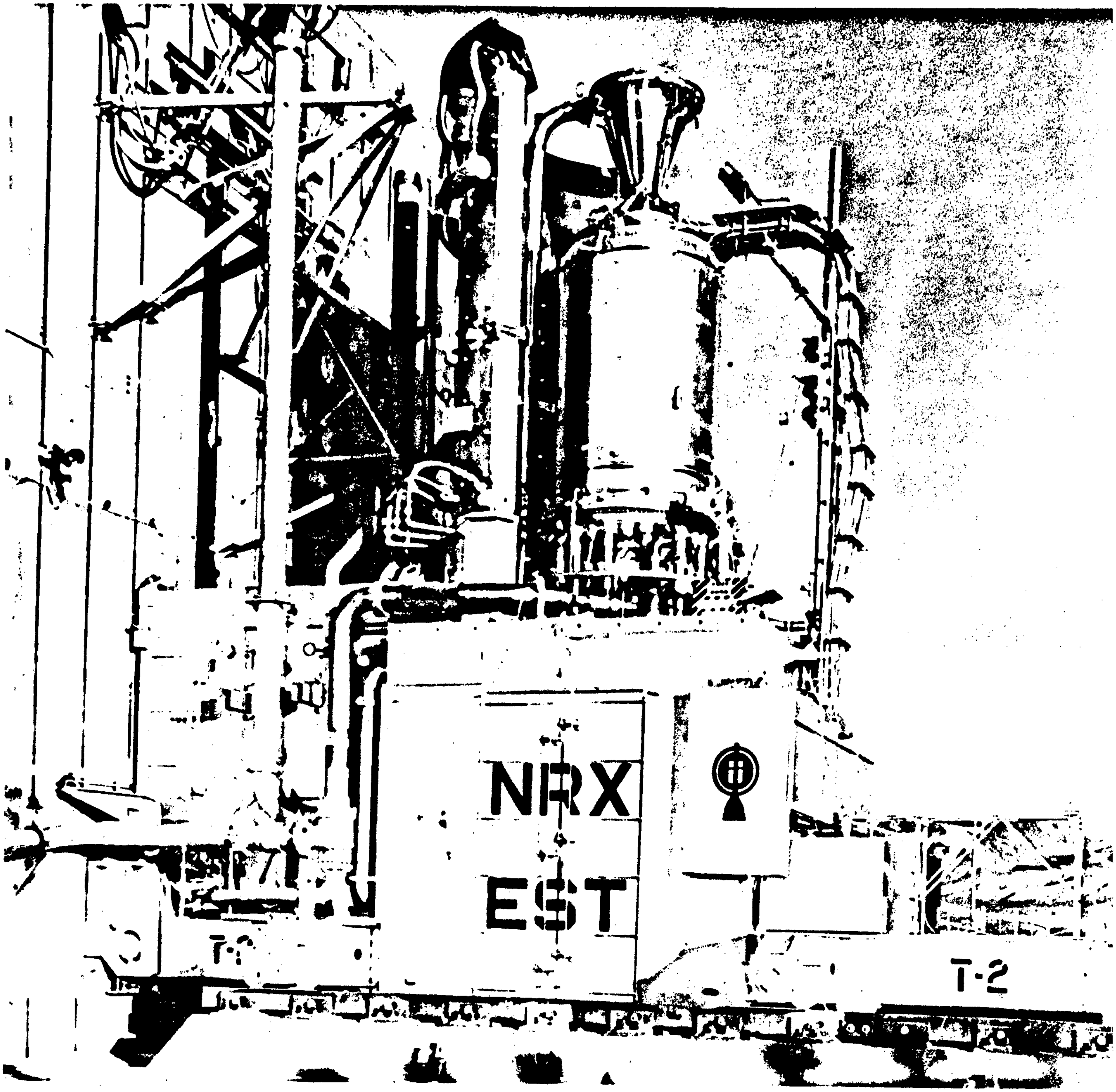


Figure 3-10. Photograph of NRX Reactor on Test Stand

Figure 3-11 demonstrates the similarity between the Pewee-1 reactor and the proposed heat source. Comparison of a number of full size reactors and Pewee operation is shown in Figure 3-12.

The thermohydraulic relationship of the reactor subsystem to the disk generator is shown in Figure 3-4 and the physical arrangement can be seen in Figure 3-5. The NERVA technology reactor as shown in these figures is closely coupled with the disk MHD generator and provides significantly lower total system launch mass for integrated (500 s) pulse and high (100 MW_e) power operation, less than half the linear MHD system studied previously.[3-3] The gas-cooled reactor is readily close-coupled directly to the MHD disk generator, eliminating the performance loss associated with the high temperature heat exchange at the reactor nozzle and generator.

The energy conversion effectiveness and recuperative thermal savings of the nuclear MHD disk generator system concept results in a low reactor thermal power requirement, ~ 262 MW. Therefore, the size of this reactor will be criticality limited rather than heat transfer surface limited. The reactor core incorporates a zirconium hydride moderator in the support elements to permit reducing the core size and uranium loading. The core size selected provides the needed neutronic reactivity enhancement with high performance composite fuel (UC ZrC-C) that permits a maximum fuel loading well within demonstrated performance and technology (< 760 mg/cm^3). Noncorrodible low density zirconium carbide thermal insulators are used to eliminate concern for H_2 corrosion. The core will be capable of substantially higher power output (350 to 400 MW_t) than that demanded of it for this mission, permitting substantially higher power levels without reactor mass increases of any significance.

The proposed reactor support components are regeneratively cooled as done in previous reactors. Although there is no demonstration of cooling the reactor with cesium seeded hydrogen, it is not considered a serious concern with the core temperature and seed control used in this application.[3-2] Any significant cesium vapor within the reactor will be cleared with

Item Description	Pewee	NERVA Derivative Reactor for MHD Power System
Design Power (MW_t)	500	350
Operating Power (MW_t)	514	261
Operating Time (min)	64	< 10
Fuel Elements (no.)	400	360
Average Power/Elem (MW_t)	1.3	0.73
Maximum ΔT, Fuel to Coolant (°C)	110	205
Maximum Fuel Temperature (K)	2860	3080
Fuel Exit (K)	2655	2970
Disk MHD Inlet (K)	N/A	2900

Figure 3-11. Comparison of Pewee-1 Reactor to NERVA Derivative Reactor

Reactor ID	Fuel Temp (K)	Time at Max. Temp. (Min.)	Shutdown
KIWI-B4D	2222	1	Hydrogen Fire
KIWI-B4E	2389	8, 2.5	Normal
NRX-A2	>2200	3.4	Normal
NRX-A3	>2400	16.3	Normal
PHOEBUS-1A	2478	10.5	Ran Tank Dry
NRX-A4 (NRX-EST)	>2400	28.6	Normal
NRX-A5	>2400	29.6	Normal
PHOEBUS-1B	2445	30	Normal
NRX-A6	2556	62.7	Normal
PHOEBUS-2A	2306	12.5	Normal
PEWEE-1	2750	43	Normal
XE-PRIME	>2400	7.8	Normal
NF-1	2450	109	Normal

Figure 3-12. NERVA Reactors Operating History

termination of seed feed since the seed is vaporized below the minimum ~ 600 K core coolant temperature level where the seed is introduced. The required valves, control actuators and liquid hydrogen pump design are based on the thoroughly tested and developed technology used in NERVA.

Although the radiation levels are nearly two orders of magnitude lower than in NERVA, some internal shielding of control and actuator components is necessary. The proposed shield design embodies zirconium hydride technology.

Small nuclear reactor designs, such as the Pewee, were studied in some depth by both Los Alamos National Laboratory (LANL) and Westinghouse late in the NERVA program. The overall reactor layout based on the Westinghouse study is shown in Figure 3-13 and a typical fuel module in Figure 3-14. Estimates of component mass and the total reactor mass based on these designs are presented in Figure 3-15. The reactor coolant flow pattern is schematically shown in Figure 3-4. It has the design features noted:

- Single-stage centrifugal pump, electrically driven
- Regeneratively cooled metal core axial support elements (tie tubes)
- Regeneratively cooled reflector and shield
- ZrH neutron moderator contained in tie tubes
- Internal radiation shield of zirconium hydride
- 360 fuel elements, (93% enriched UC_2 in composite matrix)
- Nine control drums in beryllium reflector
- Valves and valve actuators
- Titanium pressure vessel
- Overall reactor containment length = 2 m
- Overall reactor diameter = 0.87 m
- Total mass = 2200 kg

One of the outstanding features of the nuclear reactor energy source is its potential for growth in increased specific mass and performance advantages. Pure carbide (UC ZrC) fuel elements were in an early stage of development and show promise to attain reactor operating temperatures in excess of

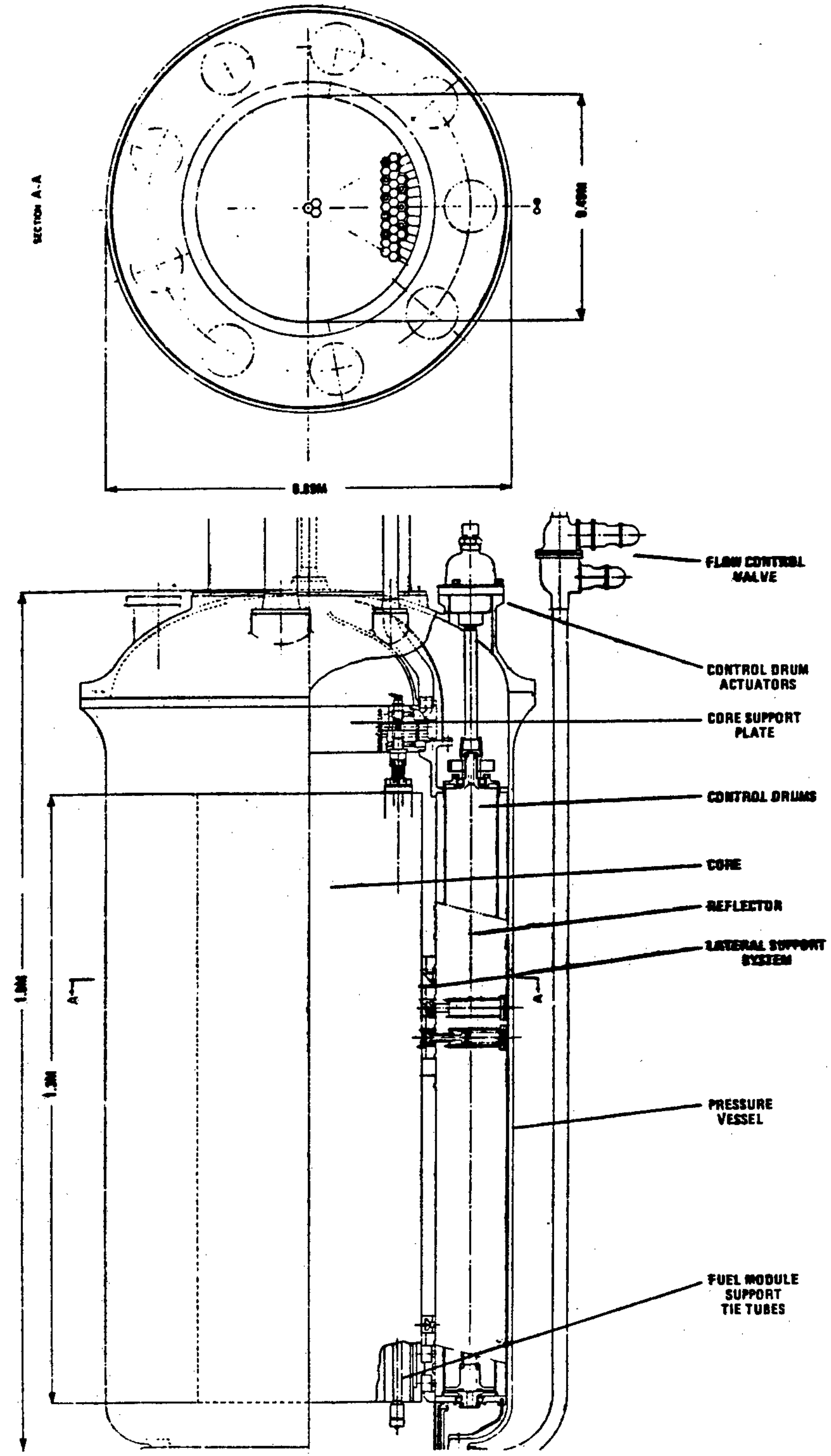


Figure 3-13. Layout of Reactor Cross Section and Elevation for Small Nuclear Engine Similar to Proposed Heat Source

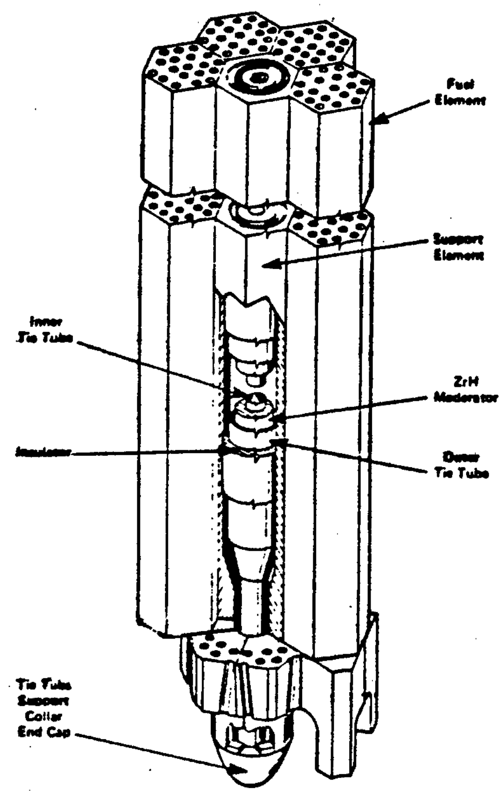


Figure 3-14. Fuel Module Concept for the NERVA Derivative Reactor

Item	Mass (kg)
Core and Support Hardware	805
Reflector, CD's and Support Hardware	595
Shield (Internal)	200
Pressure Vessel	170
Valves, Actuators and Plumbing	190
Feed Pump	40
Instrumentation and Control	150
Contingency	50
Total	2200

Figure 3-15. Reactor Mass Estimates

3100 K, with a resulting higher specific power and energy extraction. The reactor design for these new fuel elements is similar to that for the composite fuel elements, but modified to accommodate the lower thermal-stress tolerance of the carbide elements.

NUCLEAR DESIGN SAFETY CONSIDERATIONS

The core design also considers the possibility of reactivity insertions arising from accident conditions, most notably water immersion and core compaction. Immersion of the NERVA cores in water or other moderating substances significantly alters the core nuclear characteristics. Assuming that all voids in the reactor core are flooded with water upon immersion, the core reactivity increases by as much as 35% $\Delta k/k$. Consequently, an anti-criticality system is specified for the NERVA designs.

Several means of suppressing this reactivity were defined in the NERVA program and are available. The different reactors described in this study will also have differing immersion reactivity characteristics depending on core void fraction, internal control rod worth, and structural poison worths in a thermal environment. The tentative approach is to use poison (B10) wires inserted into the core. Another approach is to incorporate B_4C in the form of beads in a gel/binder material for the cores within burst capability.

The possibility of core compaction caused by explosion or launch abort impacts also exists. Core compaction of the NDR fuel region is not nearly as severe as condition as that of water immersion. By assuming that a compaction accident compresses the core uniformly eliminating all void regions, it is estimated that the core reactivity would increase no more than 10% $\Delta k/k$. Consequently, the neutron poison system, necessary for the water immersion case, is more than adequate to ensure subcriticality in the event of core compaction as well. Note that a combination of immersion and partial core compaction would entail less reactivity worth, since core compaction reduces the amount of water which can enter the core region, and therefore, neutron moderation will be less effective.

TECHNICAL ISSUES

The key technical issues, development areas, and their priorities based on (1) basic feasibility and acceptability for mission, and (2) major impact on design and system mass, (but not a feasibility or concept acceptability consideration) are noted in Figure 3-16 and discussed below.

To realize the potential operational advantages of the nuclear/MHD system, a development program would be required to extend the reactor capabilities, i.e., a temperature of 3000 K at the lower power densities required and to provide a highly ionized plasma that is compatible with the system and the space emission requirements.

Assurance that the reactor fuel can provide the design temperature is supported by the following factors:

- Demonstrated reactor performance up to 2700 K fuel temperature and higher than required power density operation data are available. Only low risk extension from demonstrated fuel/reactor performance for much shorter duration is needed (see Figure 3-16).

- Advanced Nuclear Reactor fuel nuclear environment requirements are attainable within known materials technology base from the NERVA Program.

- Reactor configuration and core support design have been demonstrated and require no development.

- Advances in both materials and component data base have been made since the NERVA Program.

- Proposed fuel element is composite (ZrC + C + Zr coated UC) with ZrC + ZrC coated UC hot end which is capable of operating up to 3250 K. (3500 K is fuel melt limit).

Issue	Priority	Solution
Demonstration of sensor, instrumentation and control reliability for long-term (10 yr) space and radiation environment	1	Develop and demonstrate temperature, neutronic and position sensors, and other electronic components that will function for long times and in high radiation levels in space environment
Demonstration of reactor capability to operate at a temperature of 3000 K and fast transients	1	Develop mini-arch fuel element hot end configuration and verify performance
Capability for reactor safe reentry	2	Conceptual design, simulation tests and verification or reactor reentry analytically demonstrated for NERVA
Capability for permanent reactor shutdown	2	Identification and development of an acceptable option for permanent reactor disposal

Figure 3-16. Reactor Heat Source Key Technical Issues and Development Areas

- Composite fuel elements at over 2700 K have operated at equivalent reactor thermal/power conditions in electric tests for 10 hours with 60 shutdown-to-full-power cycles with insignificant materials loss (< 4 g carbon), and no apparent degradation, indicating significant additional capability existed, especially for short durations (see Figures 3-17 and 3-18).

- Carbide fuel technology is understood and carbide "tips" have been demonstrated on both graphite and composite fuel elements.

- Both NRX-A6 and XE-Prime Engine reactors operated successfully and demonstrated configuration/design engineering adequate for the reactor heat source.

- The disk concept reactor is the same size as the demonstrated Pewee reactor.

Coupled with the temperature and quick response requirements and the operational/reliability advantages provided by the nuclear driven open cycle MHD for pulse power and for a long duration in space environment, there is also required materials, instrumentation and control development.

These development efforts have all been identified in other studies currently in progress or under consideration. For example, Westinghouse supported the nuclear portion of an SDI-MHD study contract at Idaho National Engineering Laboratory (INEL).[3-3] Investigation of these same issues is included in a proposal from both INEL and LANL to the Air Force Rocket Propulsion Laboratory in which Westinghouse is a participant. Thus, the NERVA derivative reactor is receiving serious attention in other quarters for electric power and propulsion applications. These other concurrent programs are expected to resolve the key NERVA-type reactor technology issues, leaving the MHD power system program in a position to devote its resources to the generator and other issues specifically related to MHD. Moreover, Task 2 will not require a nuclear power source to provide high

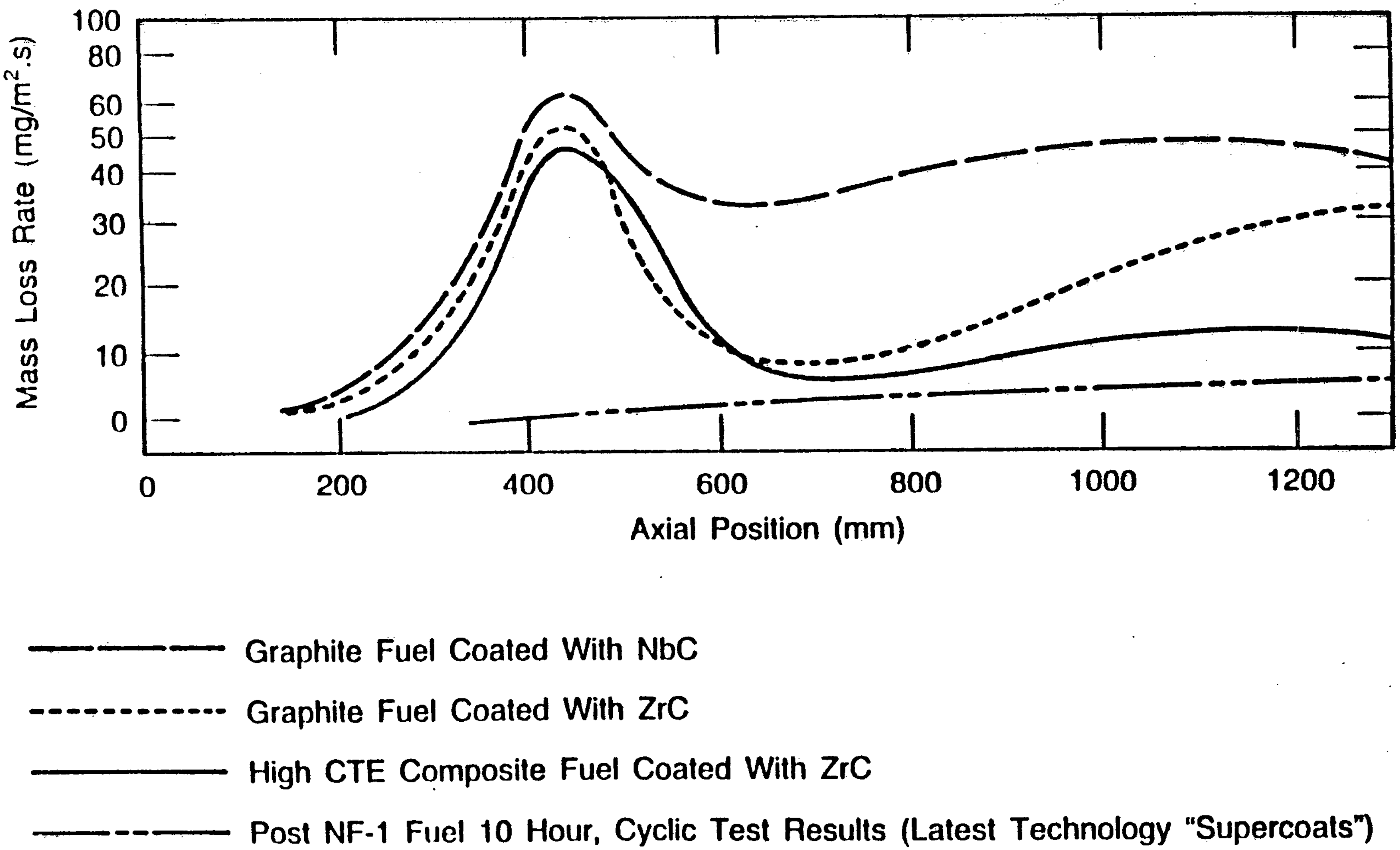


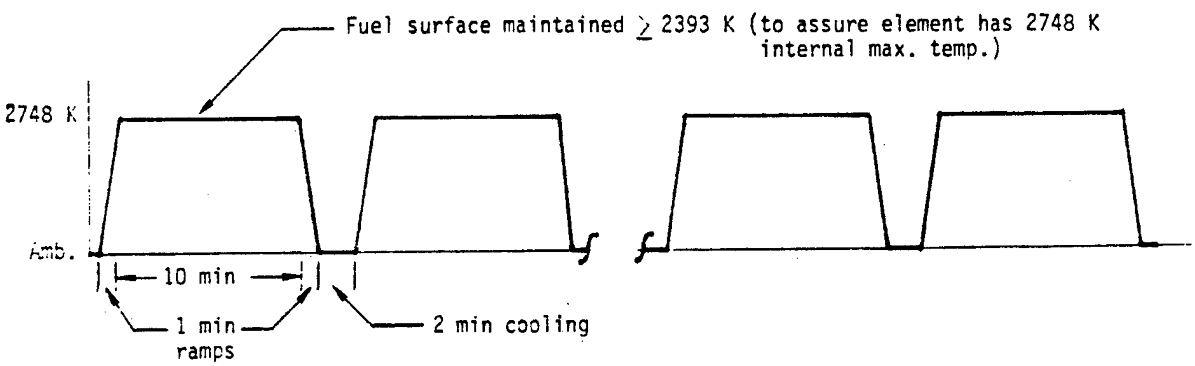
Figure 3-17. Mass Loss Rates for NERVA Fuels

POST NF-1 REACTOR FUEL ELEMENT TEST PERFORMANCE -
COMPOSITE FUEL ELEMENT - UC_2 FUELED

TEST CONDITIONS: (Test 1 C)

• Control surface temp.	2383 K
• Internal fuel temp.	2748 K
• Flow rate - H_2	500 SCFM
• Inlet pressure	(hundreds of psi)
• Inlet temp. - H_2	Ambient
• Power (to coolant)	> 0.75 MW_t*
• Test duration	> 10 hours
• Power Cycles	> 60 (4 added for good measure)

TEST PROFILE - 10 Hour Power Test



RESULTS: (Composite fuel - latest pedigree)

• Fuel Condition	Excellent
• Coating cracks	None found
• Midband corrosion	None
• Mass loss - (diffusion?)	3 - 4 gms (Total mass of element ~ 1 kg)

FUEL IMPROVEMENTS OVER NF-1 COMPOSITE FUEL

- Better match of graphite CTE with coatings
- POCO reactor grade, high quality graphite
- Coating temperature profile/deposition control (anomalously good coatings from one coating furnace!)

Note: POCO* with "normal" coatings lost only ~ 6-8 gm, but still showed no mid band corrosion

Figure 3-18. Summary - Westinghouse Electric Furnace Testing temperature seeded hydrogen to generator-related test articles; a plasma torch is suitable as the heat source without compromising test objectives.

3.1.3 Hydrogen Storage and Handling System

Liquid hydrogen is stored cryogenically in an insulated aluminum tank while the system is in orbit. When the system is operational, power from the platform system is used to refrigerate the system, essentially eliminating boil-off during this period. The refrigeration system used to cool the hydrogen storage tank is also used to cool the disk generator magnet during alert periods, maintaining it at its operating temperature of 20 K.

A total of 5260 kg of hydrogen is required to operate the power generating system over its 10 year lifetime in orbit, including a 400 s burst, for a total of 500 s full power operation. This hydrogen is stored at 20 K, at a pressure slightly below one atmosphere. With the system operating in a zero gravity environment, a system of screens is installed within the tank, utilizing capillary forces to separate the liquid phase from the vapor at the hydrogen pump and magnet cooler inlets. With such a system, it is not possible to utilize all the hydrogen in the tanks, and it is expected that 160 kg of residual hydrogen will be left in the tank at the end of operation. In addition to this, 270 kg will be lost as boil-off between launch time and the time power is available to operate the cooling system. The total hydrogen capacity of the system is therefore 5690 kg, and, with a 2% ullage allowance, the storage volume is 81 m^3. The mass of the aluminum tank including the insulation and internal fittings is 580 kg.

A liquid hydrogen flow of 5.45 kg/s is supplied to the reactor and generator system by means of an electrically driven centrifugal pump which raises its pressure to 63.3 atm. The combined mass of the pump and motor will be 392 kg, and the package is 0.40 m O.D. by 0.79 m long. The hydrogen flow supplied to the magnet for cooling is 0.078 kg/s; no pump is required for this flow.

3.1.4 Cesium Seed Storage and Handling System

Ten kilograms of cesium seed is required for the mission with a flow rate of 0.018 kg/s at full power operation. This seed is stored in liquid form in the standby mode at 650 K and a pressure of 1 atm. To maintain pressure when using seed, gas pressure is supplied to the seed storage system. A metal bellows provides separation between the seed and the pressurizing gas, insuring that the seed pump suction is fluid at all times. The seed pump provides metered flow to the seed mixer and has a discharge pressure of 50 atms.

At the seed mixer, the total pressure is 36.7 atms at 650 K. With a seed mole fraction of 5.0×10^{-5}, the partial pressure of the seed vapor is 1.8×10^{-3} atms, well below the saturation pressure of 1.7×10^{-2} atms at this temperature. The seed mixer must produce a uniform distribution of seed in the flow stream, as little mixing can take place in the flow passages within the reactor core. A series of mixing vanes are installed to further homogenize the cesium vapor/hydrogen mix.

The total volume of cesium stored is 6.1×10^{-3} m^3, and the seed tank is expected to occupy 9.1×10^{-3} m^3, including the bellows separator, required head space, and thermal insulation. The pump and gas storage is expected to occupy another 9.1×10^{-3} m^3. The mixer will be located in a widened portion of the hydrogen piping just before entering the reactor. With the exception of the pressurizing gas bottle, the cesium seed storage and handling system will be located at the top of the reactor dome.

While in the standby mode, 75 W_e will be required to maintain the cesium storage tank at 650 K and to drive the pressure and temperature controls.

3.1.5 Disk MHD Generator Description

The generator is shown schematically in Figure 3-19 and is a single radial outflow disk. Figure 3-5 shows a pictorial representation of the generator, the reactor, and the effluent system. The generator consists of a nozzle, a short relaxation zone where the gas is fully ionized, three power generating sections and the diffuser. The three power generating sections are delineated by four electrodes as shown schematically in the figure. The first two and the fourth electrodes are formed by hydrogen cooled tungsten rings set into the walls of the generator, and the supporting vanes for the two coils of the magnet form the third. The top and bottom walls of the generator are electrically insulated, preventing short circuit currents from flowing. In operation, the gas from the reactor is accelerated through a nozzle and passes through a short, open circuited relaxation zone prior to passing the first electrode and entering the active portion of the generator. In the nozzle, the gas is accelerated to M 2.4, and in the relaxation zone, the cesium seed is completely ionized prior to entering the generator.

In the first or inlet section of the generator, the thermodynamics of the nonequilibrium ionization constrain the generator loading and the current in this region is about 7000 amps. In the middle section of the generator, the plasma state permits higher loadings and 10,000 amps. A third set of electrodes, is provided at the magnet separators permitting another change of load. A constant potential exists in this region and the disk is configured to act as a nozzle, reaccelerating the plasma prior to entering the third (final outflow) section of the generator. In this section, the field is reversed and a current of 7000 amps is attained. After leaving the generator radial outflow section the plasma passes through a 180° turning vane diffuser to enter the inflow section of the disk, balancing torque before entering the effluent control chamber.

Relatively high values of recovery factor (~ 0.6) can be readily achieved in the diffuser since boundary layer blockage is minimal and the hot well

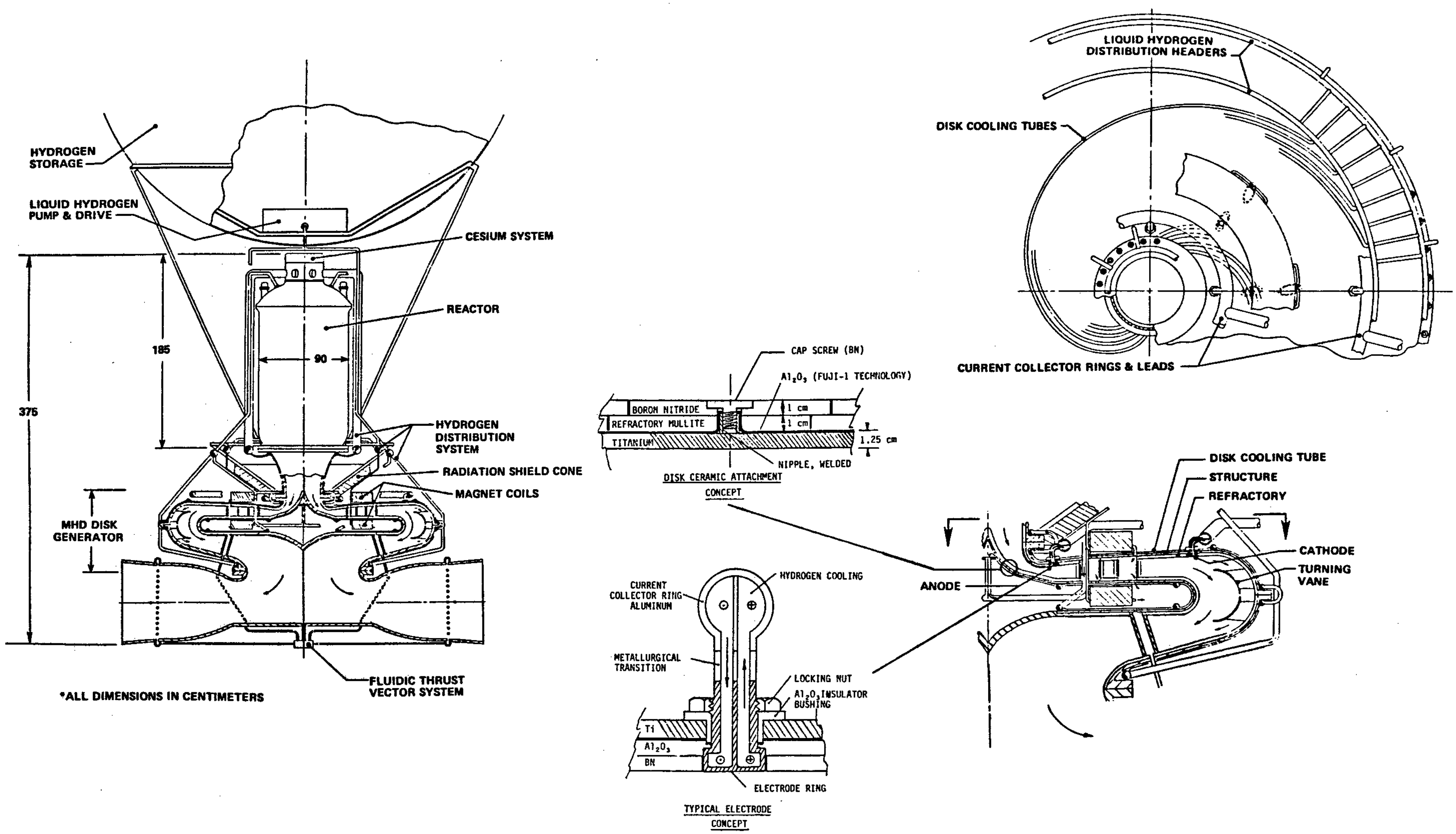


Figure 3-19. MHD Disk Generator Concept

design minimizes density and velocity differences in the flow cross-section at any radius.

Although the power generator consists of the region between the first and fourth electrodes, structurally the nozzle, relaxation zone, generator and diffuser form a continuous entity, with the contour of the gap between the upper and lower surfaces and the electrical properties of the wall tailored to perform the appropriate functions. Of the total power generated, 32% is produced in the inlet section, 51% in the middle section, and 17% in the exit section.

The inner radius of the inlet section of the generator is 0.18 m, and the generator exit to the diffuser is 0.78 m. The height of the flow passage varies from 0.045 m at the entrance to 0.15 m at the exit plane. The cesium seeded hydrogen leaving the reactor enters the generator through the nozzle and then flows radially outward. After leaving the active section of the generator, the gas flows through the diffuser, and undergoes a 180 deg turn prior to entering a lower plenum, and leaving the system. In operation, the generator behaves like an impulse turbine. The gas enters the generator at a high velocity, and for an MHD system, a low static temperature. As it travels radially outward through the generator, the static temperature remains nearly constant, and power is extracted from the kinetic energy of the gas.

The generator structure is constructed of coated titanium alloy, providing low mass while operating at temperatures in the range of 600 K. Fifty-one titanium cooling tubes are welded to the upper and lower surfaces of the generator and are arranged in a spiral pattern which maintains constant spacing between the tubes. This arrangement provides for uniform cooling with no hot spots on the structure. On the inner surface of the disk walls, a plasma sprayed coating provides a thermal barrier and a full coverage backup electrical insulator between the Boron nitride refractory insulation and the titanium structure as noted in Figure 3-19. Separation between the upper and lower surfaces of the generator and split coil separation is provided by an array of tungsten standoff vanes. These vanes support the forces due to the generator internal pressure as well as those existing between the two halves of the magnet. In addition to the structural support provided by the vanes, they serve to transport coolant to and from the cooling passages located on the lower surfaces of the generator and the upper surfaces of the exit ducting, as well as to the lower coil of the magnet. A similar set of vanes located down stream of the diffuser provides support for the exit ducting. In this region, the temperature of the plasma has been reduced to where cooling of the structure is no longer required, and the exit ducting is formed from a coated graphite composite.

In operation, the radially flowing conducting gas interacts with the axial magnetic field to produce a tangentially directed current. The velocity of the electrons traveling in the tangential direction, acting against the magnetic field produces a radial voltage gradient. When a radial current is allowed to flow, this gradient provides the useful power output from the generator. Ring-shaped tungsten current collectors are provided at the inlet and outlet ends of the generator (and two radial locations in between) to provide a path for the radial current to flow. The relationship between the radial electric field and the tangential current is dependent on the Hall parameter (β), the ratio between the electron cyclotron frequency in the magnetic field, and the mean collision frequency of the electrons, with performance increasing with increasing values of β which ranges from about 3 near the entrance of the generator to a maximum of 12.

Under normal operation conditions, the static temperature of the gas (< 1700 K) is too cold for useful ionization of the cesium seed. The selection of operating conditions for the generator is such that the ohmic heating within the gas raises the mean temperature of the electrons to over 3800 K. At this temperature, with the low partial pressure of seed, nearly 100% of the cesium is ionized, and an electrical conductivity of 30 mho/m is obtained in the plasma. The electron temperature achieved is, however, too low for significant ionization of the hydrogen to take place. With the seed completely ionized, and negligible ionization of the hydrogen, the electrical properties of the plasma are nearly independent of the local electron temperature variance over a wide range. This condition, coupled with the rapidly increasing energy losses to the hydrogen as the electron temperature increases, will minimize the chance for instabilities often associated with nonequilibrium ionization operation of an MHD generator.

Because of the interactions between the radial and tangential current densities, the electron heating is a function of the radial current density, as well as other parameters of the system. The electron temperature is at a maximum under open circuit conditions, and decreases with increasing loading. To insure that the seed is fully ionized prior to entering the generator proper, a short section of the nozzle is open circuited just prior to the anode. Recent work by Lin and Louis from Tokyo Institute experiments indicate that this configuration is fully stable and given maximum power density. For a given set of conditions of gas static temperature, pressure, and velocity, and a given magnetic field, there is a critical loading which, if exceeded, will result in a sharp drop in electron temperature below the value providing useful ionization of the seed. Louis and Lin[3-4] have also confirmed this phenomena. In general, however, high loading is required to achieve good performance of the generator. Near the entrance of the generator, conditions are such that useful over-all values of radial current density cannot be sustained. Further along the generator radius, significantly larger currents can be sustained, and a third electrode (not shown in Figure 3-19) is located in this region. This electrode permits high loading in the downstream portion of the device, where such loading can be utilized to gain high performance.

As the gas approaches the mean radius of the magnet, the magnet field reduces to zero, and changes sign. In this region, the disk forms a second nozzle, reaccelerating the gas. Downstream of the magnet, the reversed field is used to extract more energy from the gas. In this section of the generator, approximately 17% of the total power is produced. At the low pressure existing in this region, no problems are encountered with ionization of the cesium in spite of the relatively low magnitude of the magnetic field.

3.1.6 Effluent Control

The effluent control subsystem is needed to provide the functions of balancing dynamic forces and controlling the impact of the cooled exiting plasma on the local spacecraft environment. The nuclear driven disk MHD generator system will add only cesium, a condensible, to the hydrogen effluent. Aside from the question of thrust force, the effluent cloud has the potential for causing adverse effects on platform system operation and undesirable electrical effects as indicated by the unclassified information in Figure 3-20. As indicated in the table, condensibles in the effluent cloud should be avoided, but all MHD systems utilizing a gaseous working fluid require the addition of a seeding material to achieve needed levels of plasma electrical conductivity within the limits of achievable gas temperatures. This seed, usually cesium because of its low ionization potential, means an open-cycle MHD system adds charged particles, cesium ions and electrons, to the effluent. Therefore, control and management of the MHD system effluent are essential to fully utilize the advantages of open-cycle MHD systems in the SDIO mission. The low hydrogen and cesium flow rates needed with the high energy extraction rates of this design result in minimum effects.

The motion of the working fluid through the power system creates two reaction forces on the system which must be balanced. The first thrust is produced by the fluid as it exits the MHD generator and flows into space, and the second is the reaction to swirl forces in the generator induced by the interaction of the radial plasma flow and the magnetic field. Regarding the thrust forces, the effluent is divided into two equal streams as it exits the generator, and these streams are directed along the same straight line, but in opposite directions. Therefore, by this approach, nozzle experience has shown their thrusts, approximately 5.4 kN each, should nearly cancel (< 1 %). While this occurs naturally by design, it is desirable to guarantee a thrust balance by equipping the generator nozzles with an automatic flow control device.

NPB WEAPON & DISCRIMINATOR:

- Beam stripping/recharging to give H+
- Cannot fire through effluent cloud
- Plasma formation (arcing, glow, ATP)
- Thrusts (pointing)

FEL WEAPON:

- No condensibles allowed (cooled optics) - No water, O_2, etc.
- Plasma formation (as above)
- Thrusts (pointing)

EML WEAPON:

- Plasma formation (as above)
- Arcing of the rails & barrel

ATP SYSTEM:

- No condensibles allowed

Figure 3-20. Power System Effluent Effects

The swirl reactions also tend to cancel naturally due to generator design. This results from the placement of the magnet near the radial midpoint of each disk which causes the plasma to experience two opposite direction fields, and a swirl force reversal, as it flows radially in each disk. It would be unreasonable to expect an exact balance of swirl reactions by this mechanism. However, the swirl forces and the thrust reactions at the two generator exit nozzles lie in parallel planes. Therefore, a thrust-direction control feature at the nozzles with a single degree of freedom enables the cancellation of any nonzero swirl reactions.

Effluent temperature of the system that will operate with nonequilibrium ionization will be significantly lower than in equilibrium ionization MHD generators. This results in both the seed concentration and the working fluid mass flow rate requirement being minimized. In addition, hydrogen is the same effluent that will be produced by the SDIO-mission system and is relatively innocuous. The cesium, as indicated above, could be recovered in part if necessary by additional cooling in the effluent control chamber. Therefore, the environmental impact produced by the nuclear/disk generator power system is inherently relatively small in the open-cycle mode, and it could be reduced even further by incorporating appropriate auxiliary system design features.

The effluent control chamber and schematic of the conceptual fluidic control are presented in Figure 3-21. As noted, the MHD plasma will be collected near the edge of the disk through a designed turning diffuser and returned to the central axis of the disk generator where swirl and fluid motion will be redirected as a low velocity axial flow. This will then be separated into two opposite directions, exiting the effluent control chamber through fluidically balanced flow nozzles. Gas for the fluidic control is conceptually taken from the exhaust of the magnet cooling system and uniformally distributed unless control requires balance corrections. Although simple in concept, this approach to vernier control of the exiting flow will require further study in Task 2 design.

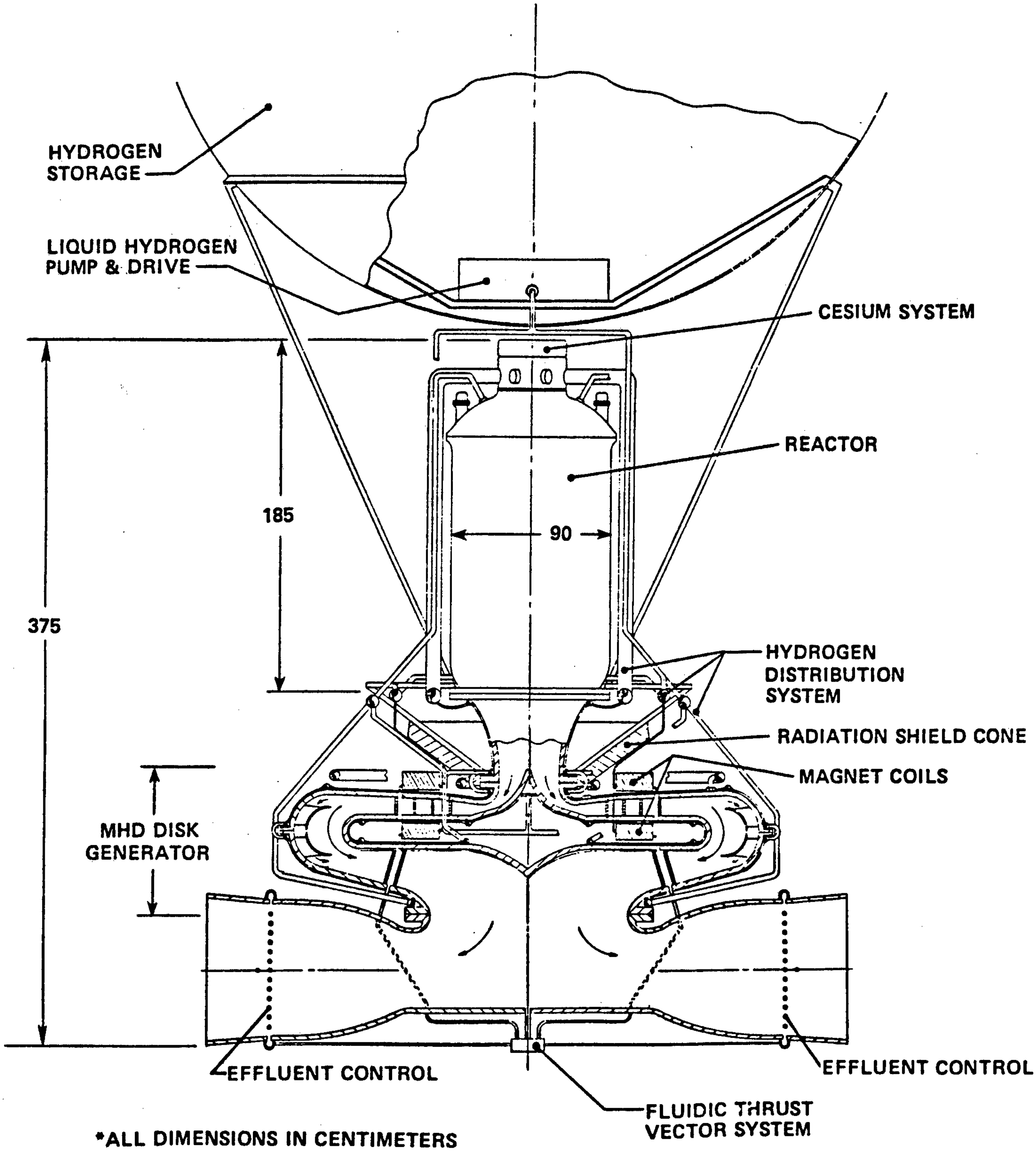


Figure 3-21. Disk Generator Effluent and Fluidic Thrust Control Schematic

The effluent chamber is constructed of composite material and at the low exit temperature and with the limited time of operation required, will be uncooled. The composite material will permit a significant limitation of nozzle generated vibration frequencies and help minimize dynamic feedback to the space platform.

3.1.7 Magnet and Associated Equipment

The major characteristics of the magnet system are summarized below:

Magnet Description	
Dimension:	2 Coils in Split Pair:
ID	0.80 m
OD	1.26 m
Height	0.18 m
Gap	0.20 m
Power Consumption	35 kW
Mass	720 kg
Coolant Flow	0.078 kg/s
Cost	
Power Supply	
Description	Batteries
Mass	100 kg

The design of the MHD disk generator permits simple construction of the magnet as a pair of single coils. The utilization of the field existing outside of the magnet to drive the outer section of the disk permits a relatively small diameter magnet to be used, realizing a significant reduction in magnet weight. The reference design magnet is constructed from state-of-the-art ultra-high purity aluminum, and consists of two circular coils with a total mass of 720 kg. Each coil has an inner radius of 0.4 m and an outer radius of 0.63 m and is 0.18 m high. The generator lies within a 0.20 m gap separating the two halves of the magnet, and the active section of the generator extends 0.15 m past the outer radius of the magnet. Figure 3-22 shows flux contours of the magnet, at the relative position of

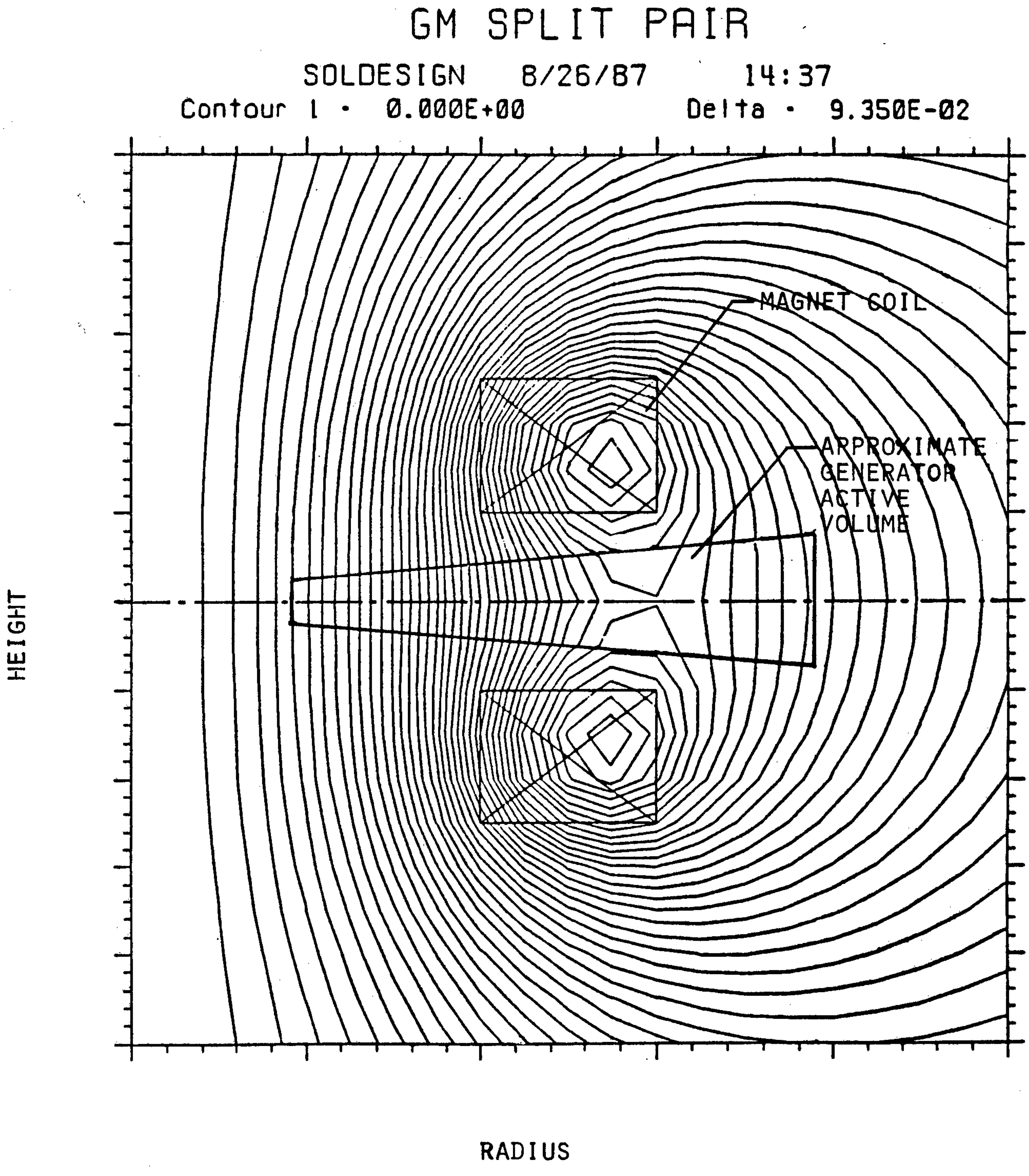


Figure 3-22. Baseline Magnet Flux Contours

the generator. With the magnet operating at 20 K it consumes 35 kW of electrical power while operating in the burst mode, which is dissipated by the heat of vaporization of a separate stream of liquid hydrogen.

The magnet will be powered by a set of onboard batteries, with a total useful energy capacity of 21 MJ or ~ 6 kW-hr. A system of onboard batteries with associated controls is required to give the initial charge to the magnet even if the magnet system were to be bootstrapped from the disk generator. In addition, bootstrapping would require a system of high voltage/high current contactors to provide the necessary switching between the magnet leads during startup and the power management system. In the interest of eliminating these contactors, and simplifying the power management system sufficient batteries will be provided to meet the magnet power needs for the entire burst. The energy required is roughly equivalent to 10 automobile batteries, and the batteries will weigh less than 100 kg.

3.1.8 Power Conditioning and Control

Power conditioning for the nuclear MHD disk generator is required to produce two output conditions for start-up and operational load requirements. As specified, the full load rating is 100 MW at 100 kV DC and, in addition to providing this output, power conditioning is also required to deliver 25 MW at 100 kV during the system start-up phase (ready mode, see Section 3.3).

Analysis of the nonequilibrium disk generator as presented elsewhere has shown that a minimum of three multiple loadings is desired to obtain the best performance. A short open-circuit entry section is also needed to establish stable nonequilibrium ionization.

It is noted that the open-circuit section has no bearing on the power conditioning but the performance requirements of the remaining sections affect the full load component selection and overload requirements in the 25% power mode.

To illustrate the power system configuration, the reference case selected was calculated to deliver 108 MW from the MHD generator and to have the following conditions on each of the three power take-off sections of the disk.

Section #	Loading (K value)*	Current A	Voltage kV	Power MW
1	0.62	7,000	5.0	35
2	0.78	10,000	5.5	55
3	0.54	7,000	2.6	18
				108

*Load current density/short circuit current density

The three sections have to be appropriately combined to provide the net output power of 100 MW, 100 kV requirement, the actual configuration being determined by the need to also meet the quarter power requirement. A straightforward method of achieving the quarter power requirement is to use the front section only for power production in the startup mode and to short circuit the remaining two power sections through their associated converters. This approach, as shown below, minimizes the mass penalty in the power conditioning system over that required for a single point load. In addition, it will provide for minimum pressure drop in the generator and, from the generator design viewpoint, will require only that the lofting be set to ensure that at quarter power, no shock penetration into the active power section can occur. Work with equilibrium generators has already established in principle how this condition can be met. In the selected design case, the power from the first section is 35 MW but a repositioning of the take-off electrode can readily reduce this to meet the 25 MW requirement.

For the conceptual design, the magnet excitation power of 35 kW is obtained from a separate battery pack, which is charged from the associated SP-100 power system. This system has the advantage of permitting magnetic field control by the interposition of a DC-DC converter between the batteries and the magnet.

The excitation of the generator magnet may be either by self or separate source excitation. In the case of equilibrium generators, a circuit developed by Velikhov and also by Maxwell and Demetriades(3-5)(3-6)(3-7) has been successfully employed with simple Faraday and diagonal generators. The circuit involves the use of an auxiliary source which provides the initial magnetic field from which the generator can bootstrap itself in the required full magnetic field condition. Application of this principle to the nonequilibrium disk driven from a nuclear source raises additional issues as follows:

- Self-excitation can, in principle, proceed either from initial equilibrium or nonequilibrium ionization, depending on reactor conditions.

- The magnet must be connected to the Hall terminals from which current can only be drawn when a significant Hall parameter is established.

- Full excitation can only be reached with nonequilibrium ionization in the disk generator.

These concerns require analysis beyond the scope of Task 1 and will be addressed in the next stage of the project. This discussion has identified major uncertainties in applying self-excitation to the nonequilibrium generator and implies that a trade off study with separate excitation is required assuming a successful circuit which will require additional power conditioning.

The selected power conditioning configuration is shown in Figure 3-23 and a single line diagram for a converter appears in Figure 3-24. The basic

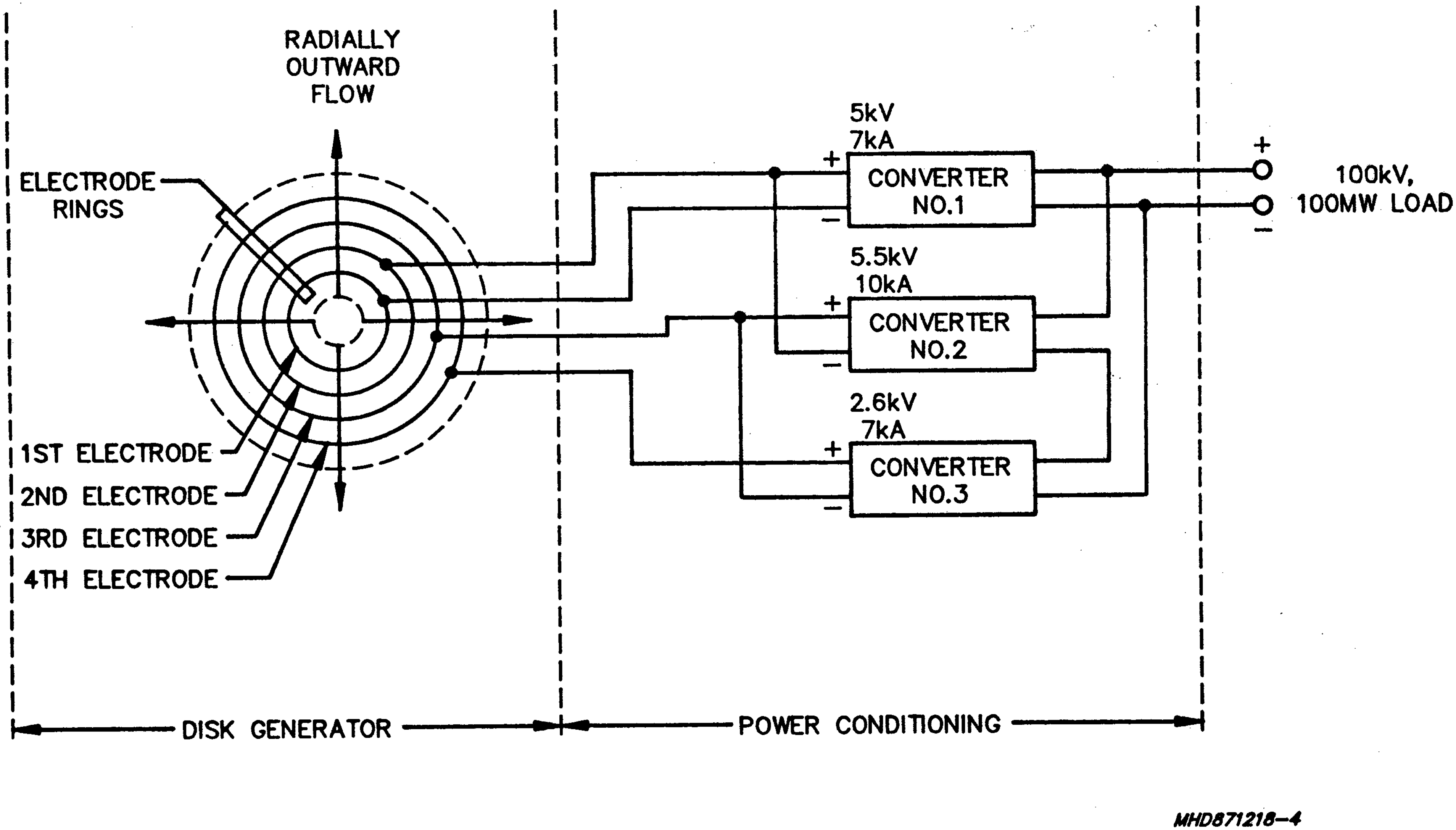


Figure 3-23. Power Conditioning System Configuration

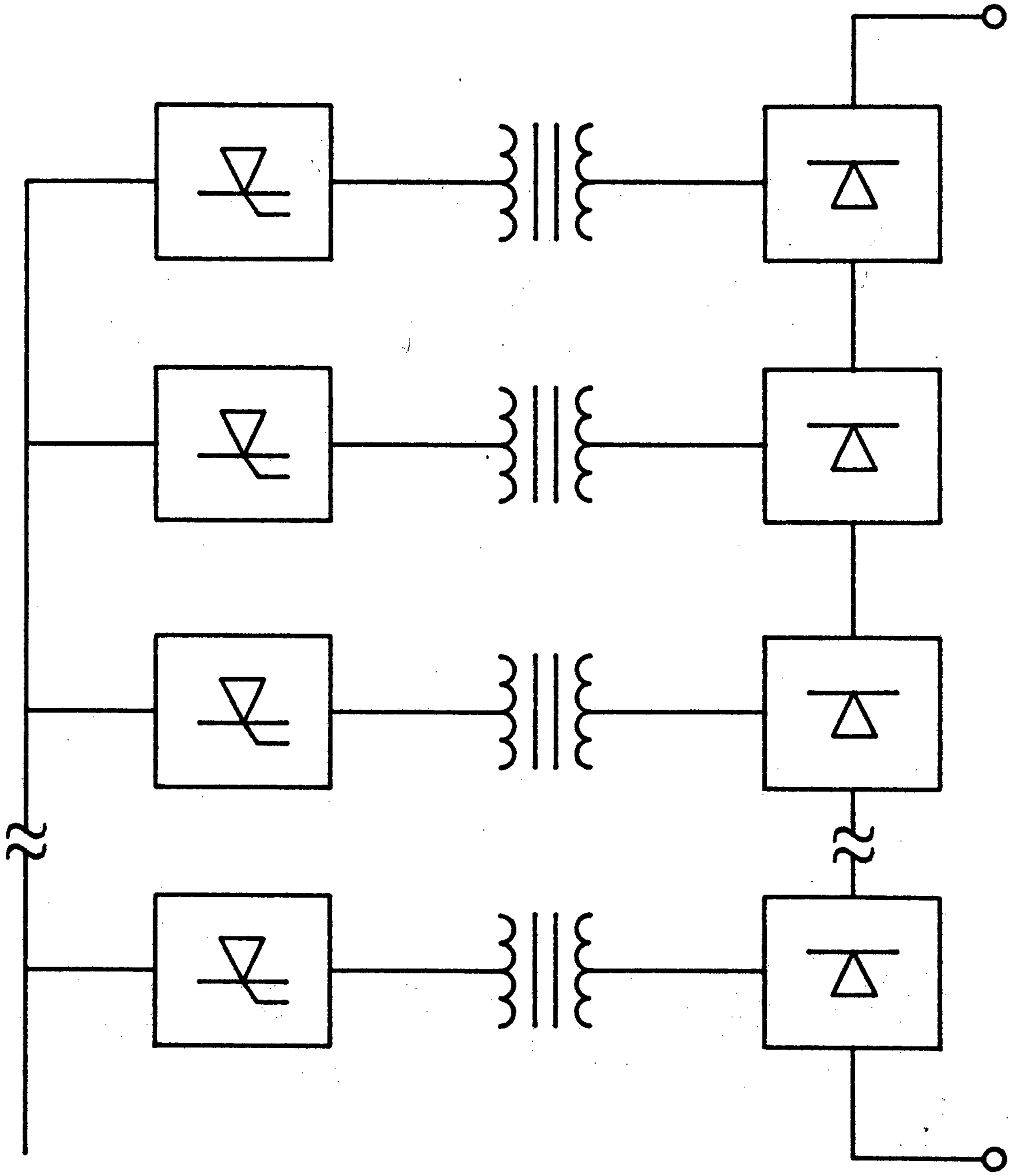


Figure 3-24. Converter Single Line Diagram

arrangement is to connect the outputs of the second and third power sections in series and to parallel these with the output of the first section. This enables the full voltage output to be provided by the first section converter when the other two are in the short-circuit mode during startup and in the ready mode. The actual series connections are made through the rectifiers on the high voltage side to avoid applying identical instantaneous constraints to the high voltage transformer windings. Compared with the series connection which would otherwise be used, this imposes a voltage penalty on the rectifiers and doubles the required rectifier capacity. The resulting power conversion system mass is about 12% greater than for a design for single point loading. Quarter load operation may impose additional penalties since the active devices in sections 2 and 3 have to be capable of handling the short-circuit current. For section 2 this is a 30% penalty on the rectifier but for section 3 involves a doubling of their rating. The mass penalty for this component is an additional 16% for single point loading. However, operation at short-circuit, as shown in the generator performance calculations, can be expected to lead to the lower conductivity mode of operation. In this case, no rating increase will be needed and the 16% penalty can be avoided.

Each converter would comprise a single-phase bridge rectifier with its own transformer. An initial estimate of the number of converters required for the 3 sections are 5, 8 and 5 respectively. The transformers would either be stacked to support the 100 kV potential difference or have appropriately graded insulation. The optimum arrangement can only be arrived at in a detailed design study. The proposed configuration is completely consistent with the anticipated power conditioning mass numbers derived from the SPA results. A detailed design study is needed to establish the mass distribution between the several components and particularly to resolve the amount allocated to packaging. For this preliminary investigation, the "near-term improvement" value of 0.253 kg/kW is considered reasonable and has been used in the associated system studies.

3.1.9 Cooling and Heat Rejection Subsystems

OPERATION

For the main system, cooling is accomplished regeneratively during normal operation. The hydrogen working fluid is pumped through the cooling system and heated significantly prior to being mixed with the cesium seed and entering the reactor upper plenum. At this point, the hydrogen is at approximately 650 K and 37 atm, well above the saturation pressure of the cesium. After leaving the hydrogen pump and the power conditioning system, the cold gas is directed to the reactor tie tubes and support structure. The dense hydrogen gas in the tie tubes acts as a moderator for neutrons, and the temperature/density relation for this gas field introduces a negative reactivity coefficient, enhancing the reactor stability. In this region, the hydrogen absorbs about 28 MW of thermal energy, raising its temperature from 23K to 43 K.

After leaving the tie tubes and support structure, the flow is directed to cool the reflector reactor control drums and the reactor vessel. In this region, the gas absorbs another 7.5 MW_t, raising its temperature to 415 K. The gas exiting the reflector cooling passages leaves the reactor vessel and is used to cool the electrical leads connecting the generator to the power conditioning system. About 3 MW_t is dissipated within these leads, raising the coolant temperature to 567 K. The coolant flowing in these leads is also used to cool the tungsten electrodes in the disk generator. Except for these electrodes, the interconnecting plumbing forming the cooling system is aluminum up to this point, as are the electrical leads. After leaving the electrical leads, the remainder of the cooling system plumbing is titanium tubing.

After cooling the electrical leads, the gas is directed to the disk generator to control the generator wall temperature. In this region, the cooling channels are oval titanium tubes welded to the surface of the generator structure. The tubes are arranged in a spiral pattern, providing a constant tube spacing at all locations on the disk surface. This arrangement provides uniform cooling over the disk surface, eliminating hot spots near the disk periphery. In addition, it accommodates thermal expansion of the components easily. The final component cooled by the main flow of working fluid is the lower plenum at the reactor exit. Again, the coolant is led through a series of a parallel cooling passages on the surface of the plenum and is collected in a common header prior to being mixed with the cesium seed and entering the reactor. At this point, the hydrogen is 650 K, well above the saturation temperature of cesium at a molar concentration of 0.005%.

For proper operation, the magnet material temperatures must be maintained at 20 K with hydrogen stored at 20 K, and heated to 25 K by the hydrogen pump. This stream is then used to cool the power conditioning system electronics. At the exit of the power conditioning system, the coolant has been heated to 73 K. It was found to be impractical to cool the magnet with the main stream of hydrogen. Instead, a separate stream of low pressure liquid hydrogen is directed to the magnet, which is vaporized within the magnet. After leaving the magnet, this coolant provides the working fluid for the thrust control system.

STANDBY

In the standby mode, no cooling is required for the majority of the system components. The equilibrium temperature for the system in orbit will be well within safe limits for all components. The electronics package will have to be insulated and/or have sufficient thermal capacity installed to insure that expected temperature swings do not exceed the allowable range. Approximately 50 W of heat will have to be supplied to the cesium supply to maintain its operating temperature of 650 K. The magnet will have to be maintained at its operating temperature of 20 K. This will require extracting approximately 120 W_t at this temperature. It is expected that much of this heat loss will be by conduction to the surrounding structure, as the large operating loads seen by the magnet will require a strong structure support. An additional 110 W of thermal energy must be extracted from the hydrogen storage tank to prevent boiling off the stored hydrogen during the period in orbit. The refrigeration system to cool both of these components will require 23 kW of electric power, most of which must be radiated. A radiator area of 1.8 m^2, operating at 400 K, will be sufficient for this application.

3.2 System Performance

3.2.1 Overall System

The system is designed to provide 100 MW_e of conditioned DC power to the load over a total accumulated time of 500 s. The gross electrical power produced by the MHD disk generator is 108.4 MW_e, and Figure 3-25 summarizes the overall system performance. Of the generator output, 2.6% is dissipated in the system wiring, particularly in the tungsten leads to the electrodes. An additional 4 MW_e is lost in the power conditioning system. This system includes the power conversion system as well as the power supply for the pumps, heaters, and control elements. The hydrogen pump requires 706 kW_e, and the cesium pump and heater combined consume 0.11 kW_e. Approximately 70 kW_e is allocated to drive the valves and other control elements. An additional 35 kW_e is supplied to the magnet system from an onboard battery power supply.

The net electrical power at the power conditioning system (100.8 MW_e) allows for 0.8 MW_e transmission loss between the power system and the weapons system. In addition to the electrical performance of the system, Figure 3-25 also shows typical flows during operation. Evaluation of the generator performance has indicated that best performance occurs with a seed molar concentration of 5×10^{-5}, corresponding to 0.33% seed on a mass basis. This extremely low concentration (approximately 1/3 of the initial estimate), reduces the potential problem of cesium contamination to a minimum.

Figure 3-26 is a flow schematic diagram with statepoints identified by the circled numbers. Conditions at these statepoints are tabulated in

Electrical Performance	
Gross DC Power at Terminals	108.4 MW_e
Power Conditioning System Loss	4.0 MW_e
Resistance Loss in Leads	2.8 MW_e
Pump and Auxiliaries	0.8 MW_e
Net Power to Load Leads	100.8 MW_e
Electrical Efficiency	93%
Flows and Thermal Performance	
Hydrogen Flow to Reactor	5.45 kg/sec
Cesium Flow to Reactor	0.018 kg/sec
Total Reactor Flow	5.47 kg/sec
Hydrogen Flow for Magnet Cooling	0.078 kg/sec
Total Hydrogen Flow	5.53 kg/sec
Reactor Thermal Input	261 MW_t
Energy Extraction	42%

Figure 3-25. MHD Disk Generator Performance Summary

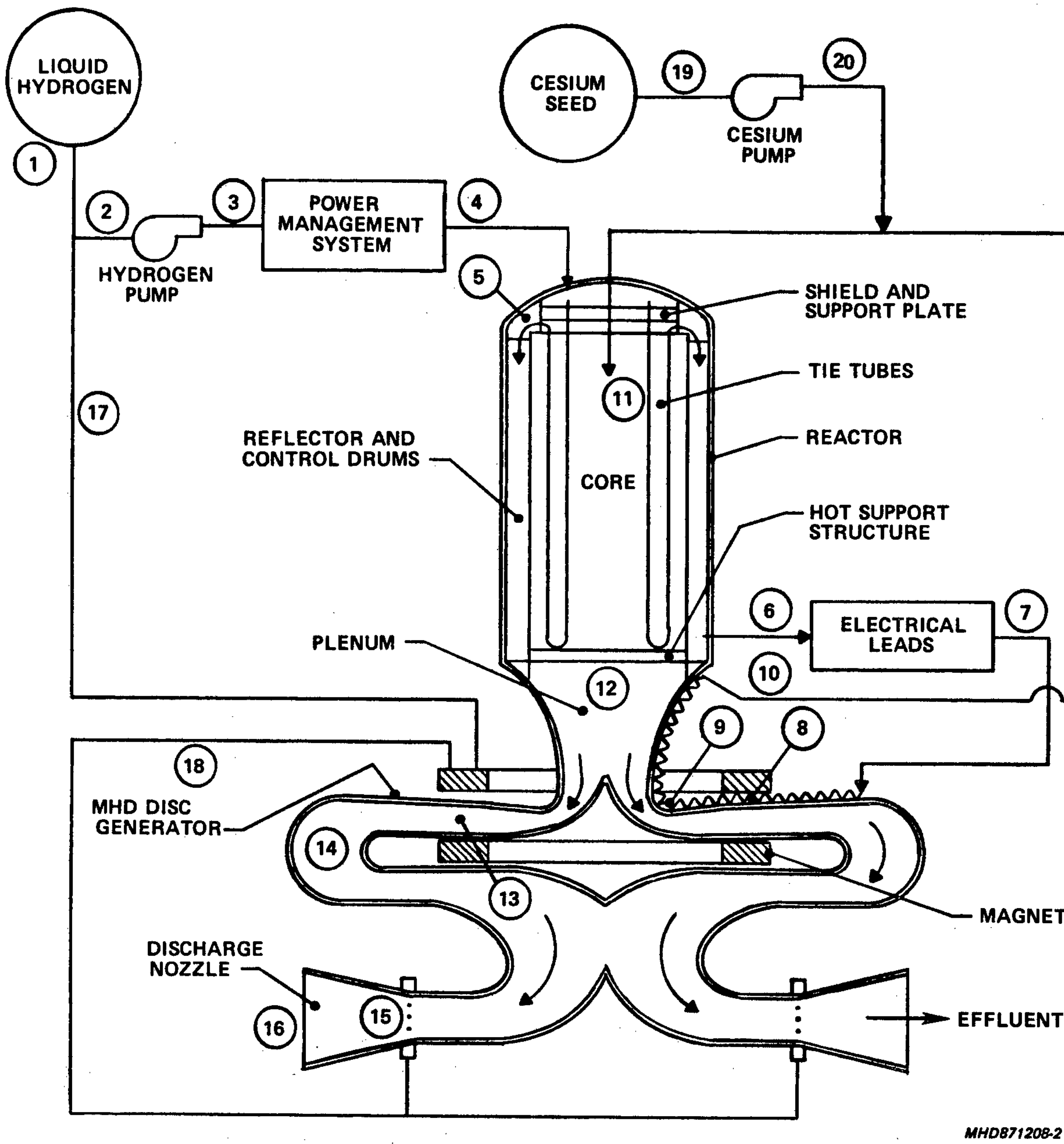


Figure 3-26. Power System Schematic Showing Statepoints

Figure 3-27. The temperatures and pressures given in this table represent total or stagnation values except the stressed values at the exit. The temperature at state point 12, the inlet nozzle to the disk generator, is as high as practicable to obtain maximum performance for the disk generator. The temperature of 2900 K is consistent with good operation of the generator, as well as within the capabilities of the reactor. The pressure at this point (16.6 atmospheres) represents a reasonable level on the basis of Mach No.s, generator size and performance. At higher pressures higher Mach No. are possible in keeping with the electron mobility in the gas and the Hall parameter of the generator. Lower pressure does not result in large improvements in performance, but does increase the size of the generator and its associated ductwork.

DISK GENERATOR (Statepoints 12, 13 and 14)

Although the disk generator is physically a radial outflow disk, it is divided electrically into three sections. The first two sections are located within the magnet radius, and the magnetic field varies between 4T and 3.5T. The combined electrical output of these two sections is 83% of the total power produced ~ 90 MW_e. The third or exit section lies outside the magnet radius and extracts significant amounts of power from the magnet return field. In this section the peak field is reversed at -1.3T and decreases with increasing radius. In this section, the gas velocity, temperature and pressure are low compared with conditions in the entrance and middle regions. At the low pressures in this region, the electron mobility is high, and, even with the low field, Hall parameters ranging between 4 and 6 can be obtained, adequate for good performance. This section produces an additional 18 MW_e of electrical power or about 17% of the total.

Near the magnet, the magnetic field goes through zero and changes sign. In this region little power is generated, and the channel serves as a nozzle, accelerating the gas prior to entering the outboard section of the

#	Location	C_s Mol Fr	W (kg/s)	P_{tot} (Atm)	T_{tot} (K)
1	H_2 Tank Outlet	0	5.530	1.00	20
2	H_2 Pump Inlet	0	5.452	1.00	20
3	Power Conditioning System Cooler Inlet	0	5.452	63.2	27
4	Core Support Structure Cooler Inlet	0	5.452	61.2	73
5	Reflector and Control Drum Cooler Inlet	0	5.452	51.2	413
6	Electrical Lead Cooling Inlet	0	5.452	46.6	532
7	2nd Section Disk Generator Cooler Inlet	0	5.452	45.6	567
8	1st Section Disk Generator Cooler Inlet	0	5.452	41.6	576
9	Reactor Lower Plenum Cooler Inlet	0	5.452	37.6	613
10	Seed Mixer Inlet	0	5.452	36.6	650
11	Reactor Core Inlet	5.0×10^{-5}	5.470	36.6	650
12	Disk Generator Inlet Nozzle	5.0×10^{-5}	5.470	16.6	2900
13	2nd Section Disk Generator Inlet	5.0×10^{-5}	5.470	0.71	2170
14	Thrust Vector Control Section Inlet	5.0×10^{-5}	5.470	0.25	1880
15	Exit Nozzle Inlet	4.9×10^{-5}	5.548	0.25	1850
16	Effluent Flow	4.9×10^{-5}	5.548		
17	Magnet Cooler Inlet	0.0	0.078	1.0	20
18	Effluent Thrust Vector Control Inlet	0.0	0.078	0.8	20
19	Cesium Pump Inlet	1.0	0.018	1.0	650
20	Seed Mixer Inlet	1.0	0.018	50	679

Figure 3-27. System Statepoint Conditions

generator. In the second section, the magnetic field is distributed starting at 1.3 T. Although these values are low compared with those in the entrance region, the low pressure, and resulting high electrons mobility produces Hall parameters ranging from 4 to 6, adequate for good performance of this section of the generator.

The disk generator is a Hall machine, and operates at static gas temperatures in the range of 1520 K to 1630 K. The generator operates by accelerating the gas through a nozzle to a high velocity initially. The kinetic energy of the gas is then extracted by the magnetohydrodynamic forces to produce useful energy, slowing the gas as it travels along the generator radius. With this type of operation, the gas static temperature is nearly constant in each section of the generator, although the pressure decreases rapidly. As a Hall machine, the useful radial electric field is not primarily generated by the cross product of this field and the radial component. Instead, a circulating tangential current is generated in the plasma, and the interaction between this current and the magnetic field is utilized to generate the radial electric field. The dot product of this radial electric field and the radial component of the current represents the useful power extracted from the generator. As the open circuit radial electric field is generally proportional to the Hall parameter, good performance of this type of generator requires large values of the Hall parameter. For useful power extraction, the generator cannot be operated in an open circuit condition, and a radial current must be allowed to flow. With increasing radial current, the internal resistance of the gas reduces the electrical field, and thus the power extraction. For any given value of Hall parameter and swirl, an optimum value of current loading (radial current/short circuit radial current) exists to extract the maximum power from the gas, with a corresponding best local electrical efficiency. This varies with radius. For high values of the Hall parameter, this loading and corresponding local efficiency is found near 80 percent.

The static temperature noted above is too low for significant fractions of the seed to be ionized, even at the low fraction of seed contained in the working gas. The energy dissipated in the gas by the radial and tangential components of current, however is exhibited by raising the effective temperature of the electrons carrying the current to much higher levels than the bulk gas static temperature. These energetic electrons ionize a much larger fraction of the seed than would otherwise occur. Under electron temperature conditions above 3800 K, nearly all the seed is ionized, and the gas is a good conductor.

The achievable electron temperature is a function of the current loading, the Hall parameter, the gas velocity, and the total temperature of the gas. The need to maintain high electron temperature restricts the current loading which can be utilized. The balance between the heating necessary to maintain a given electron temperature and the energy dissipated in the gas represents a complicated, non-linear relationship between the parameters mentioned. Figure 3-28 illustrates the phenomena involved. In this figure, the ordinate represents the energy dissipated in the gas for a given set of conditions, expressed as an electron temperature. The abscissa is the actual electron temperature, and the diagonal line, the locus of equilibrium points.

For the curves shown in the figure, the gas radial velocity, static pressure and temperature and the magnetic field strength are fixed, and the electron heating is plotted as a function of electron temperature for selected values of radial current. For open-circuit operation, only one solution exists and the highest electron temperature achievable exists. By permitting small values of radial current to flow, the equilibrium electron temperature is reduced somewhat. If, however, the curve is extended toward the lower values of electron temperatures, a minimum appears in the electron heating calculation. For temperatures below this minimum, the conductivity falls off rapidly, and the heating resulting from the prescribed currents rises extremely rapidly. Above this point, the characteristics of the curve are a combination of the variation in the relatively slow varying values of the gas properties, and the resulting changes in the values of the tangential component of current density.

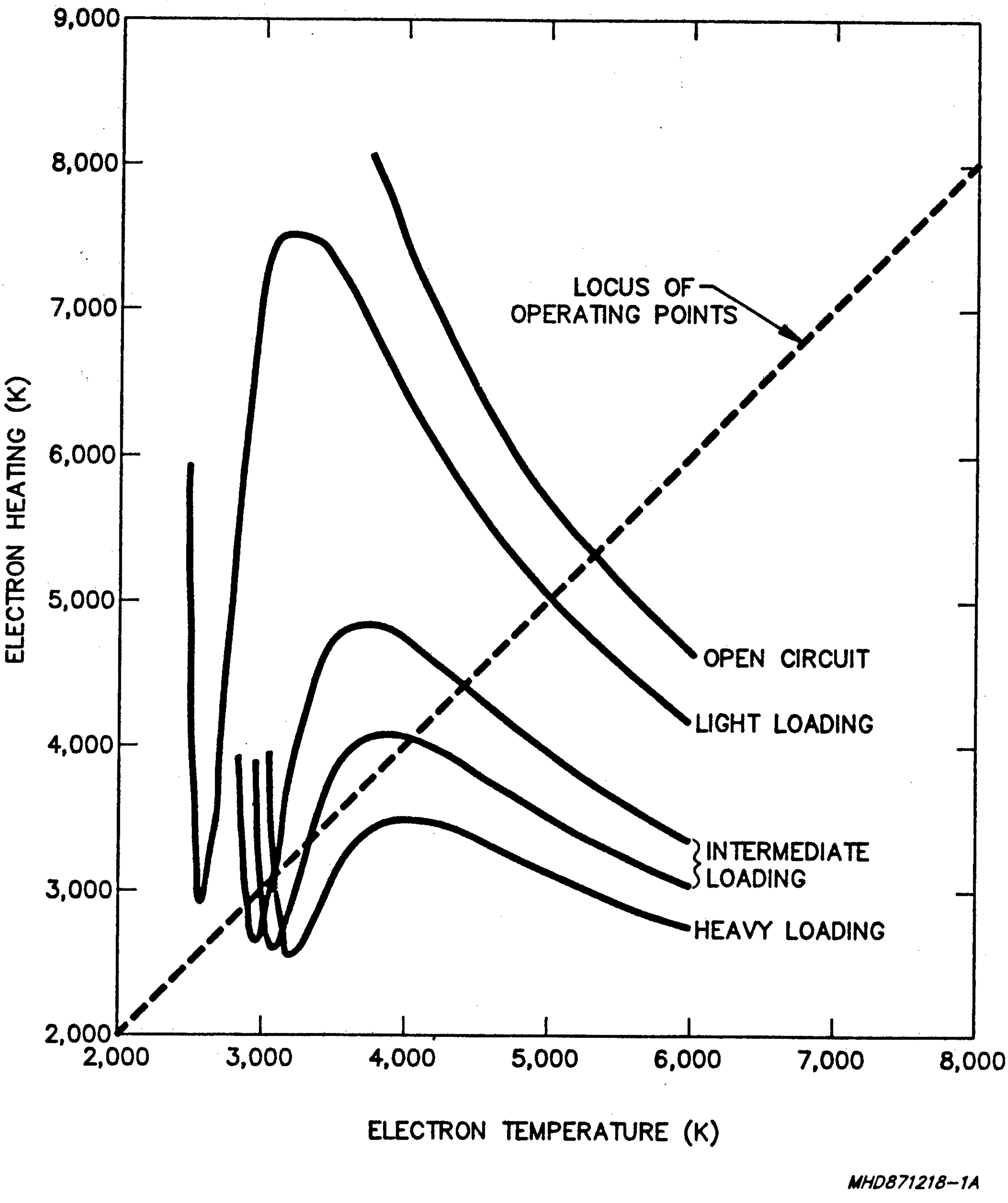


Figure 3-28. Electron Heating as a Function of Electron Temperature

For increased loading, the minimum crosses the locus of equilibrium points, and 3 values of electron temperatures are possible. Of these, the highest temperature solution is stable for disturbances which are not too large in magnitude. The middle solution is by nature unstable and would be difficult to observe experimentally. The lowest value is also stable except for extremely large disturbances. Of the two stable solutions, the higher temperature solution provides for nearly complete ionization of the seed, and represents the desired operating mode for the generator. The low stable mode, in general, represents fairly low ionization of the seed, with corresponding local instabilities in the plasma. Further increases in current loading change the characteristic of its heating curve until, for high loading, the higher temperature solution disappears, and only the low temperature solution remains.

As stated above, the curves shown in Figure 3-26 are for fixed values of the operating parameters of the generator, including a fixed value of the magnetic field ß. As such, each of the points on the curves represent distinct values of the Hall parameter (ß) of the local current loading of the channel. Figure 3-29 illustrates a more generalized relationship, relating local current loading to the Hall parameter to achieve a specified electron temperature of 3800 K.

In this case, the gas stagnation temperature is 2900 K, and no swirl is assumed. The gas velocities shown cover the range seen in the generator, and decreasing velocities produce lower useful loading. To produce electron temperatures higher than 3800 K, lower loadings would be required, as would be required for stagnation temperatures lower than 2900 K for the generator in this report. The Hall parameter near the entrance of the inlet section is 3.4 and increases to 12.6 near the magnet. In the second section, where the stagnation temperature is around 1200 K, the Hall parameter ranges from 5.2 to 6.6.

To accommodate the conflicting requirements between high current loading to achieve high energy extraction, and low loading near the entrance to

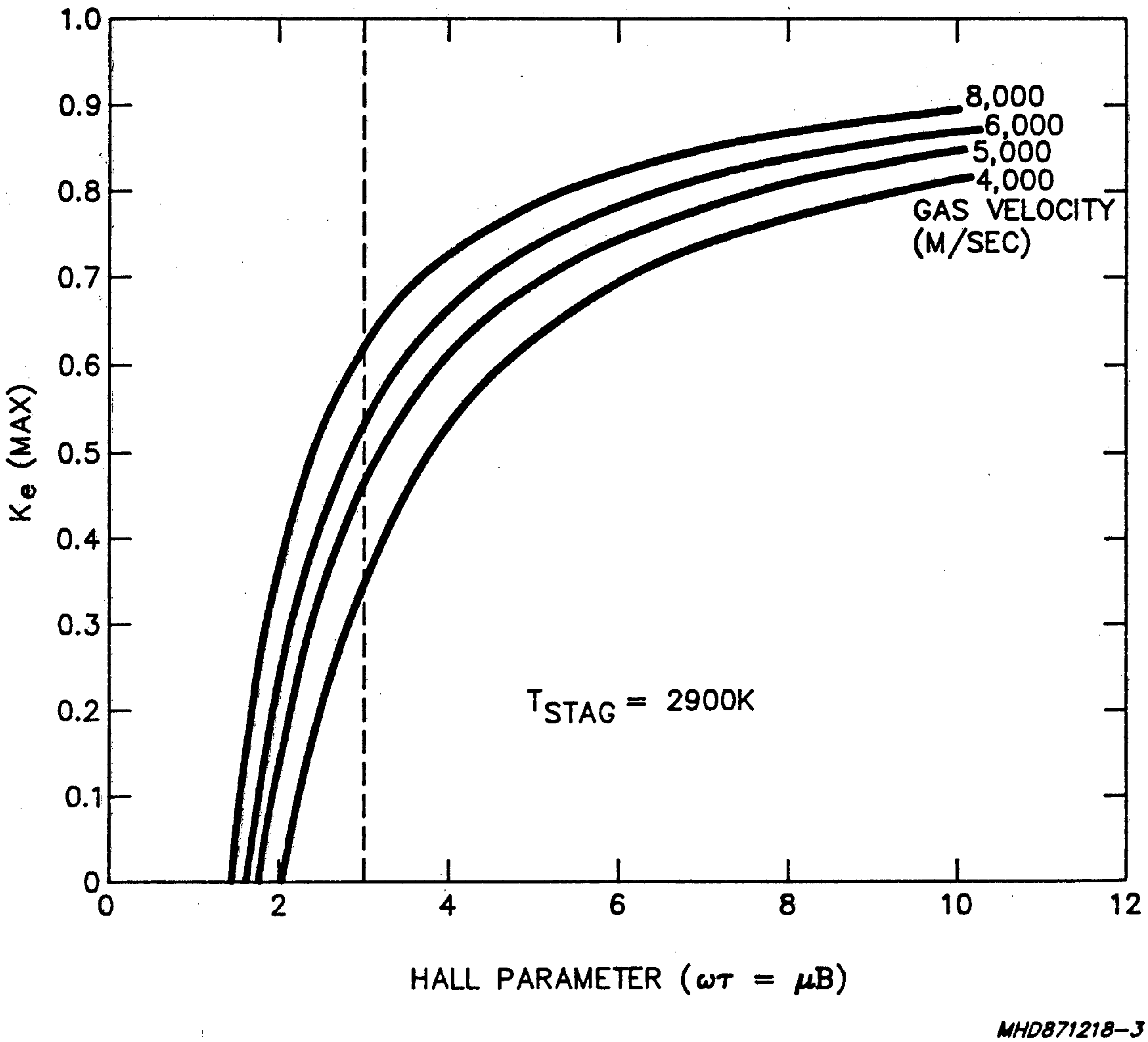


Figure 3-29. Current Loading Factor for 3800 K Electron Temperature

maintain the electron temperature with the relatively low Hall parameter of 3.5, an additional electrode is installed in the first section of the generator to permit increased loading in the region where the Hall parameter is large. At the region of the magnet, a third electrode permits the down stream portion of the generator to operate at a reduced load. At the present state of design, the inlet current is 7130 amps, with 9800 amps in the central portion, and 6850 amps in the section outside the magnet radius.

In summary, the generator produces a combined power of 108.4 MW_e, of which 85% is generated in the combined loads applied to the front 2 sections, and the remaining 15% is extracted outside the radius of the magnet. The operating conditions of the generator have been selected to maximize the energy extracted while maintaining a geometry suitable for launch. The change in stagnation between state points 12 and 13 represent the 91.7 MW_e extracted from the inlet section of the generator plus 2.9 MW_t of heat lost through the generator walls to the cooling system. In addition to the 16.7 MW_e generated in the outboard section of the generator, the temperature difference between statepoints 13 and 14 include a heat loss of 0.7 MW_t. Figures 3-30 and 3-31 show typical internal parameters of the inboard and outboard sections of the channel.

REACTOR CORE (Statepoints 11 and 12)

The reactor core exit conditions (12) are specified as 2900 K, and the pressure level required to provide best operation of the generator. The pressure drop through the core is dictated by the core geometry, the flow rate and the operating temperature and pressure. The inlet temperature to the core, 650 K at Statepoint 11, was selected by the need to insure the seed is vaporized prior to entering the core. The core pass supplies 220 MW_t out of the total 260 MW_t heat from the reactor.

	Radius (m)	Height (m)	Static Pressure (Pa)	Static Temp (K)	Velocity (m/s)	Mach Number (-)	Swirl (-)
1	0.18295	0.43858E-01	0.10100E+06	1623.9	7170.2	2.4000	0.00000
2	0.19295	0.45572E-01	93186.	1624.0	7092.3	2.3739	-0.71543E-02
3	0.20295	0.47779E-01	85530.	1624.2	7008.1	2.3458	-0.14125E-01
4	0.21295	0.50510E-01	78134.	1624.3	6917.3	2.3154	-0.20978E-01
5	0.22295	0.53834E-01	71045.	1624.5	6819.4	2.2827	-0.27775E-01
6	0.23295	0.57856E-01	64286.	1624.7	6713.6	2.2473	-0.34574E-01
7	0.24295	0.62724E-01	57857.	1624.9	6599.8	2.2092	-0.41404E-01
8	0.25295	0.63648E-01	51774.	1625.1	6475.2	2.1675	-0.48400E-01
9	0.26295	0.74804E-01	46676.	1625.3	6344.0	2.1236	-0.56152E-01
10	0.27295	0.77487E-01	44286.	1625.5	6222.7	2.0830	-0.66245E-01
11	0.28295	0.79682E-01	42359.	1625.6	6107.5	2.0445	-0.76185E-01
12	0.29295	0.81306E-01	40786.	1625.7	6008.9	2.0115	-0.85073E-01
13	0.30295	0.83198E-01	39246.	1625.7	5906.2	1.9771	-0.94177E-01
14	0.31295	0.85367E-01	37744.	1625.8	5799.5	1.9414	-0.10354
15	0.32295	0.87821E-01	36285.	1625.9	5688.8	1.9044	-0.11323
16	0.33295	0.90580E-01	34870.	1626.0	5573.9	1.8659	-0.12330
17	0.34295	0.93666E-01	33499.	1626.1	5454.7	1.8260	-0.13381
18	0.35295	0.97109E-01	32172.	1626.2	5331.5	1.7848	-0.14482
19	0.36295	0.10093	30892.	1626.4	5203.9	1.7421	-0.15643
20	0.37295	0.10520	29660.	1626.5	5071.2	1.6976	-0.16878
21	0.38295	0.10994	28474.	1626.6	4934.1	1.6518	-0.18193
22	0.39295	0.11523	27333.	1626.7	4791.6	1.6041	-0.19609
23	0.40295	0.12115	26239	1626.8	4643.9	1.5546	-0.21140
24	0.41295	0.12778	25192.	1626.9	4491.0	1.5035	-0.22806
25	0.42295	0.13524	24190.	1627.1	4332.6	1.4504	-0.24635
26	0.43295	0.14366	23236.	1627.3	4168.7	1.3956	-0.26649
27	0.43710	0.14748	22853.	1627.3	4099.0	1.3723	-0.27565

Figure 3-30. Internal Parameters of Inboard Section (Sheet 1)

	Stagnation Pressure (Pa)	Stagnation Temperature (K)	Density (kg/m^3)	Electrical Conductivity (mho/m)	Electron Mobility (1/T)	Hall Parameter (-)	Reynolds Number (-)
1	0.16025E+07	2914.7	0.15132E-01	29.697	0.84794	3.3918	0.71837E+06
2	0.14150E+07	2889.8	0.13961E-01	29.492	0.90007	3.6003	0.69134E+06
3	0.12387E+07	2863.4	0.12813E-01	29.103	0.96084	3.8433	0.65942E+06
4	0.10753E+07	2835.5	0.11704E-01	28.611	1.0301	4.1205	0.62381E+06
5	0.92544E+06	2805.5	0.10641E-01	28.054	1.1087	4.4346	0.58535E+06
6	0.78900E+06	2773.3	0.96275E-02	27.451	1.1977	4.7907	0.54474E+06
7	0.66583E+06	2738.8	0.86637E-02	26.809	1.2990	5.1961	0.50255E+06
8	0.55480E+06	2700.8	0.77519E-02	30.112	1.6591	6.6362	0.45929E+06
9	0.46326E+07	2659.5	0.69877E-02	29.648	1.7942	7.1767	0.42163E+06
10	0.40848E+06	2620.8	0.66294E-02	29.457	1.8753	7.5012	0.40726E+06
11	0.36505E+06	2586.9	0.63407E-02	30.165	2.0246	7.0862	0.39631E+06
12	0.33299E+06	2563.2	0.61048E-02	30.062	2.0900	7.3149	0.38866E+06
13	0.30306E+06	2539.1	0.58740E-02	29.955	2.1599	7.5596	0.38011E+06
14	0.27525E+06	2514.6	0.56490E-02	29.846	2.2342	7.8198	0.37078E+06
15	0.24951E+06	2490.0	0.54303E-02	29.739	2.3130	8.0955	0.36078E+06
16	0.22576E+06	2465.0	0.52182E-02	29.635	2.3962	8.3867	0.35019E+06
17	0.20392E+06	2439.8	0.50128E-02	29.536	2.4841	8.6942	0.33910E+06
18	0.18389E+06	2414.3	0.48139E-02	29.442	2.5769	9.0190	0.32755E+06
19	0.16559E+06	2388.5	0.46222E-02	29.357	2.6746	9.3612	0.31567E+06
20	0.14883E+06	2362.2	0.44375E-02	29.284	2.7778	9.7224	0.30345E+06
21	0.13360E+06	2335.4	0.42598E-02	29.221	2.8867	10.103	0.29101E+06
22	0.11971E+06	2307.8	0.40890E-02	29.174	3.0017	10.506	0.27834E+06
23	0.10710E+06	2279.2	0.39251E-02	29.144	3.1233	10.931	0.26553E+06
24	95649.	2249.3	0.37681E-02	29.135	3.2520	11.382	0.25262E+06
25	85257.	2217.7	0.36180E-02	29.148	3.3883	11.859	0.23968E+06
26	75808.	2183.3	0.34749E-02	29.189	3.5328	12.365	0.22669E+06
27	72133.	2167.8	0.34176E-02	29.215	3.5954	12.584	0.22132E+06

Figure 3-30. Internal Parameters of Inboard Section (Sheet 2)

	Electric Field (V/m)	J Radial (A/m^2)	J Tangential (A/m^2)	Power Density (W/M^3)*	Integrated Power (W)	Loading Factor (-)	Electron Temperature (K)
1	-37691.	0.14139E+06	-0.37174E+06	-0.53290E+10	0.00000	0.61209	3983.9
2	-40825.	0.12902E+06	-0.37193E+06	-0.52671E+10	0.27992E+07	0.59928	4172.7
3	-43918.	0.11700E+06	-0.36601E+06	-0.51382E+10	0.58191E+07	0.59072	4366.7
4	-47125.	0.15047E+06	-0.35684E+06	-0.49704E+10	0.90629E+07	0.58442	4573.5
5	-50531.	94521.	-0.34578E+06	-0.47763E+10	0.12542E+08	0.57946	4798.1
6	-54203.	84175.	-0.33347E+06	-0.45625E+10	0.16273E+08	0.57536	5044.8
7	-58212.	74446.	-0.32031E+06	-0.43337E+10	0.20257E+08	0.57185	5318.7
8	-35728.	89832.	-0.18144E+06	-0.32095E+10	0.24560E+08	0.78871	3937.1
9	-39877.	79393.	-0.18169E+06	-0.31624E+10	0.29039E+08	0.77854	4170.9
10	-41211.	73753.	-0.17814E+06	-0.30395E+10	0.33079E+08	0.77655	4250.2
11	-31723.	69187.	-0.15177E+06	-0.21948E+10	0.36840E+08	0.78640	3946.7
12	-32592.	65490.	-0.15026E+06	-0.21345E+10	0.39993E+08	0.78395	4001.7
13	-33383.	61898.	-0.14317E+06	-0.20660E+10	0.43277E+08	0.78203	4052.6
14	-34116.	58388.	-0.14567E+06	-0.19919E+10	0.46536E+08	0.78050	4100.4
15	-34796.	54999.	-0.14286E+06	-0.19138E+10	0.49913E+08	0.77925	4145.1
16	-35430.	51722.	-0.13981E+06	-0.18325E+10	0.53355E+08	0.77823	4187.0
17	-36017.	48560.	-0.13655E+06	-0.17490E+10	0.56857E+08	0.77739	4225.9
18	-36560.	45511.	-0.13313E+06	-0.16639E+10	0.60422E+08	0.77670	4261.8
19	-37050.	42580.	-0.12957E+06	-0.15776E+10	0.64042E+08	0.77613	4294.0
20	-37478	39758.	-0.12587E+06	-0.14901E+10	0.67694E+08	0.77569	4321.6
21	-37844.	37051.	-0.12206E+06	-0.14022E+10	0.71399E+08	0.77535	4344.8
22	-38133.	34449.	-0.11814E+06	-0.13136E+10	0.75123E+08	0.77512	4362.1
23	-38338.	31953.	-0.11410E+06	-0.12250E+10	0.78871E+08	0.77498	4372.9
24	-38447.	29562.	-0.10996E+06	-0.11365E+10	0.82635E+08	0.77495	4376.2
25	-38445.	27271.	-0.10571E+06	-0.10484E+10	0.86404E+08	0.77502	4370.9
26	-38314.	25079.	-0.10135E+06	-0.96087E+09	0.90167E+08	0.77522	4355.4
27	-38218.	24197.	-99504.	-0.92477E+09	0.91723E+08	0.77534	4345.7

*Negative sign indicates adequate joule heating of electrons and net electric power generated.
Postive sign indicates current being absorbed as joule heating.

Figure 3-30. Internal Parameters of Inboard Section (Sheet 3)

	Radius (m)	Height (m)	Static Pressure (Pa)	Static Temp (K)	Velocity (m/s)	Mach Number (-)	Swirl (-)
1	0.55000	0.10866	22424.	1566.9	4253.5	1.4500	0.20000
2	0.56000	0.10758	22209.	1566.8	4254.1	1.4502	0.19206
3	0.57000	0.10887	21726.	1566.8	4261.9	1.4375	0.18607
4	0.58000	0.11037	21235.	1566.8	4178.3	1.4244	0.18026
5	0.59000	0.11203	20742.	1566.8	4138.7	1.4109	0.17459
6	0.60000	0.11386	20249.	1566.8	4098.0	1.3971	0.16906
7	0.61000	0.11585	19759.	1566.8	4056.4	1.3829	0.16365
8	0.62000	0.11799	19273.	1566.8	4013.8	1.3684	0.15836
9	0.63000	0.12031	18792.	1566.8	3970.1	1.3535	0.15316
10	0.64000	0.12280	18316.	1566.8	3925.5	1.3383	0.14807
11	0.65000	0.12700	17735.	1566.8	3857.3	1.3151	0.14392
12	0.66000	0.12884	17355.	1566.8	3823.7	1.3036	0.13862
13	0.67000	0.12873	17144.	1566.8	3811.9	1.2996	0.13306
14	0.68000	0.13035	16829.	1566.8	3777.8	1.2880	0.12843
15	0.69000	0.13208	16512.	1566.8	3742.8	1.2761	0.12388
16	0.70000	0.13395	16195.	1566.8	3706.9	1.2638	0.11938
17	0.71000	0.13595	15880.	1566.8	3670.3	1.2514	0.11495
18	0.72000	0.13812	15566.	1566.8	3632.9	1.2386	0.11056
19	0.73000	0.14042	15254.	1566.8	3594.7	1.2256	0.10621
20	0.74000	0.14287	14945.	1566.8	3555.8	1.2124	0.10190
21	0.75000	0.14547	14640.	1566.7	3516.1	1.1989	0.97612E-01
22	0.76000	0.14822	14338.	1566.7	3475.6	1.1851	0.93349E-01
23	0.77000	0.15114	14040.	1566.7	3434.4	1.1710	0.89104E-01
24	0.77964	0.15411	13757.	1566.7	3393.8	1.1572	0.85022E-01

Figure 3-31. Internal Parameter of Outboard Sections (Sheet 1)

	Stagnation Pressure (Pa)	Stagnation Temperature (K)	Density (kg/m^3)	Electrical Conductivity (mho/m)	Electron Mobility (1/T)	Hall Parameter (-)	Reynolds Number (-)
1	75307.	2091.4	0.34925E-02	17.137	4.4371	5.7683	0.30243E+06
2	74607.	2091.4	0.34590E-02	30.784	3.9465	5.1304	0.30502E+06
3	71658.	2083.0	0.33838E-02	30.923	3.9982	5.1977	0.30106E+06
4	68726.	2074.3	0.33074E-02	30.963	4.0639	5.2831	0.29669E+06
5	65841.	2065.4	0.32305E-02	30.962	4.1370	5.3780	0.29200E+06
6	63015.	2056.2	0.31538E-02	30.934	4.2157	5.4804	0.28704E+06
7	60261.	2046.9	0.30775E-02	30.888	4.2991	5.5888	0.28187E+06
8	57580.	2037.3	0.30018E-02	30.830	4.3870	5.7031	0.27651E+06
9	54977.	2027.5	0.29269E-02	30.762	4.4791	5.8229	0.27099E+06
10	52449.	2017.5	0.28527E-02	30.686	4.5756	5.9483	0.26529E+06
11	49158.	2002.2	0.27622E-02	16.976	5.6455	6.2101	0.25635E+06
12	47354.	1995.0	0.27031E-02	17.015	5.7701	6.3472	0.25251E+06
13	46522.	1992.5	0.26702E-02	31.076	5.1044	5.6148	0.25244E+06
14	44950.	1985.5	0.26212E-02	31.130	5.1720	5.6892	0.24925E+06
15	43397.	1978.4	0.25718E-02	31.148	5.2476	5.7723	0.24586E+06
16	41871.	1971.1	0.25225E-02	31.147	5.3288	5.8617	0.24229E+06
17	40375.	1963.8	0.24733E-02	31.133	5.4148	5.9563	0.23858E+06
18	38912.	1956.3	0.24244E-02	31.109	5.5050	6.0555	0.23475E+06
19	37482.	1948.7	0.23758E-02	31.077	5.5993	6.1593	0.23078E+06
20	36090.	1941.1	0.23278E-02	31.040	5.6972	6.2669	0.22673E+06
21	34735.	1933.3	0.22802E-02	30.999	5.7987	6.3786	0.22259E+06
22	33418.	1925.5	0.22333E-02	30.955	5.9039	6.4943	0.21837E+06
23	32138.	1917.5	0.21869E-02	30.908	6.0127	6.6139	0.21407E+06
24	30939.	1909.8	0.21427E-02	30.862	6.1210	6.7332	0.20987E+06

Figure 3-31. Internal Parameter of Outboard Sections (Sheet 2)

	Electric Field (V/m)	J Radial (A/m^2)	J Tangential (A/m^2)	Power Density (W/M^3)*	Integrated Power (W)	Loading Factor (-)	Electron Temperature (K)
1	3416.6	18500.	7367.1	0.63207E+08	0.00000	1.1921	2718.1
2	-12241.	18353.	-70878.	-0.22466E+09	-11312.	0.56413	3422.2
3	-12647.	17816.	-72762	-0.22532E+09	0.85461E+06	0.55669	3491.9
4	-12921.	17273.	-73391.	-0.22319E+09	0.17431E+07	0.55246	3544.4
5	-13150.	16728.	-73514.	-0.21997E+09	0.26489E+07	0.54950	3590.8
6	-13355.	16185.	-73339.	-0.21614E+09	0.35700E+07	0.54726	3633.9
7	-13544.	15646.	-72962.	-0.21191E+09	0.45044E+07	0.54552	3675.0
8	-13724.	15114.	-72436.	-0.20741E+09	0.54516E+07	0.54412	3714.7
9	-13896.	14588.	-71796.	-0.20271E+09	0.64110E+07	0.54299	3753.2
10	-14064.	14069.	-71066.	-0.19786E+09	0.73830E+07	0.54206	3791.1
11	3141.6	13393.	5893.4	0.42076E+08	0.88375E+07	1.2319	2676.8
12	3104.0	13002.	5649.2	0.40358E+08	0.95564E+07	1.2314	2674.5
13	-10210.	12814.	-55788.	-0.13083E+09	0.98118E+07	0.56195	3420.4
14	-10412	12474.	-56305.	-0.12987E+09	0.10528E+08	0.55798	3462.6
15	-10572.	12132.	-56446.	-0.12826E+09	0.11258E+08	0.55517	3498.4
16	-10710.	11792.	-56373.	-0.12629E+09	0.11997E+08	0.55301	3530.8
17	-10834.	11454.	-56157.	-0.12409E+09	0.12745E+08	0.55128	3560.7
18	-10948.	11118.	-55838.	-0.12173E+09	0.13502E+08	0.54985	3589.1
19	-11056.	10786.	-55439.	-0.11925E+09	0.14267E+08	0.54864	3616.3
20	-11158.	10458.	-54977.	-0.11669E+09	0.15039E+08	0.54762	3642.4
21	-11254.	10134.	-54462.	-0.11405E+09	0.15817E+08	0.54675	3667.4
22	-11346.	9815.3	-53904.	-0.11137E+09	0.16602E+08	0.54600	3691.6
23	-11434.	9500.9	-53308.	-0.10864E+09	0.17393E+08	0.54535	3715.0
24	-11516.	9202.5	-52704.	-0.10597E+09	0.18162E-08	0.54481	3736.6

*Negative sign indicates adequate joule heating of electrons and net electric power generated. Postive sign indicates current being absorbed as joule heating.

Figure 3-31. Internal Parameter of Outboard Sections (Sheet 3)

STRUCTURAL COOLING (Statepoints 7, 8, 9 and 10)

The surfaces of the structures are maintained within the temperature limits of the material by circulating the hydrogen working fluid through cooling tubes on these surfaces. The interior surfaces of the components are insulated to control the heat flux. Because the cooling is regenerative, and 650 K must be maintained at the seed mixer, minimizing the heat loss through these surfaces is not the objective. Evaluation of the generator operation indicates that its performance is not significantly effected by the heat loss. The heat transfer is based on keeping an inner wall temperature of ~ 1300 K.

ELECTRICAL LEADS (Statepoints 6 and 7)

Of the 108.4 MW_e provided by the generator, 2.6% (or 2.8 MW_t) is dissipated in the electrical leads connecting the generator to the power conditioning system, the tungsten electrodes and their connectors. These leads are made of large diameter aluminum tubing, and the pressure drop will be small.

REACTOR SHIELD CONTROL DRUMS AND SUPPORT STRUCTURE (Statepoint 4, 5 and 6)

Of the total reactor power, 3.6% (or 9.4 MW_t) will be absorbed by the hydrogen within the reflector region which contains the control drums. This heat is proportional to the reactor power level. Within wide limits, the support structures, and particularly the tie tubes, can be designed to transport a specified amount of heat. For this system, the heat has been selected to be 28.5 MW_t to provide the necessary temperature at the cesium mixer.

POWER CONDITIONING SYSTEM (Statepoints 3 and 4)

The power conditioning system contains the power conversion system as well as the power consolidation system. These systems provide appropriate loadings for the generator, while matching the load characteristics of the weapons. Of the 105.6 MW_e available after the losses in the leads, 4.0 MW_e (3.8%) is dissipated in this system, which raises the coolant temperature by nearly 50 K.

HYDROGEN PUMP (Statepoints 2 and 3)

The hydrogen pump is 70% efficient, and requires 706 kW_e to raise the hydrogen pressure from 1 atm to 63.2 atm. The pump motor is cooled by the flowing hydrogen, and the total energy input to the pump raises the gas temperature by 7 K.

MAGNET COOLER (Statepoints 17 and 18)

The magnet requires 0.078 kg/s of hydrogen flow to maintain its cryogenic temperature at the level required for its operation. The coolant is vaporized within the magnet, to provide cooling at constant temperature.

INTEGRATED FLOW REQUIREMENTS

The statepoints discussed above apply to operation of the system at full power. When operating at part power, the hydrogen flow rate will be nearly the same as at full power to obtain proper velocity distribution within the generator. During the lifetime of the system, up to 20 test cycles will be performed as shown in Figure 3-3. In each test cycle, the reactor is brought up to temperature, operated for a few seconds, and shut down. In order to protect the tie tubes and support structure, sufficient hydrogen must be introduced to the reactor to cool it from a mean core temperature of 2260 K to 700 K. Each test requires 80 kg of hydrogen for cool-down in addition to 60 kg required for carrying out the test. At the end of the battle phase, an additional 230 kg of hydrogen is required to cool the reactor, and to remove decay heat. Figure 3-32 summarizes the onboard mass of consumables required to carry out the operational profile. The total cesium requirement of 10 kg is negligible compared with the hydrogen.

On Station	
Test Cycle	
Hydrogen	
Test Run	61.0 kg
Reactor Cool-Down	78.0 kg
Total Per Test Cycle	139.9 kg
Total for 10 Years on Station	2772 kg
Cesium	
Total Seed for 10 Years	2.3 kg
400 Second Battle	
Hydrogen	
Battle and Startup	2251 kg
Decay Heat Removal	233 kg
	2484 kg
Cesium	
Battle and Startup	7.2 kg
Total Consumed	
Hydrogen	5256 kg
Cesium	9.5 kg
Residual and Evaporation	
Hydrogen	428 kg
Cesium	0.5
Total	
Hydrogen	5684 kg
Cesium	10.0 kg

Figure 3-32. Consumable Requirements

Of the total hydrogen consumed, less than 43% is expended in the battle. Of the rest, 23% is consumed in test operation, and the remaining 34% is required to cool the reactor.

3.2.2 Parametric Analysis of Disk MHD Generator System

OVERALL SYSTEM

Parametric system analysis provides the means to establish the "best possible" design for the system. The Westinghouse-developed System Performance Analysis (SPA) computer program was modeled for the reference system and applied in Task 1112 for this effort. The system functional elements were identified, requirements defined and relationships established during this task. The power system design requirements imposed by the space power system mission were defined in Task 1110 by application of a top-down systems engineering approach. The background of sensitivity assessments from system parametric studies provided the basis for establishing that system requirements for the reference disk MHD generator concept were less sensitive than other conversion systems due to attractive scaling relations. The resulting reference disk MHD generator geometry and statepoint data are illustrated in Figure 3-26. The factors affecting the selected design conditions are discussed in this section.

The principal factors that affected the disk MHD generator design geometry and performance that were considered in this task were (1) the heat source and materials maximum temperature limitations, (2) stable regimes of key operating parameters of current loading, seed fraction, magnetic field and pressure, and (3) flow velocity (Mach No.).

PARAMETRIC ANALYSIS

A well defined power system concept was developed as noted in Figure 3-5. These elements were combined into a suitable system model as illustrated in Figure 3-33. The SPA system model was defined from this system element integration, but required a more cumbersome and somewhat restricted disk

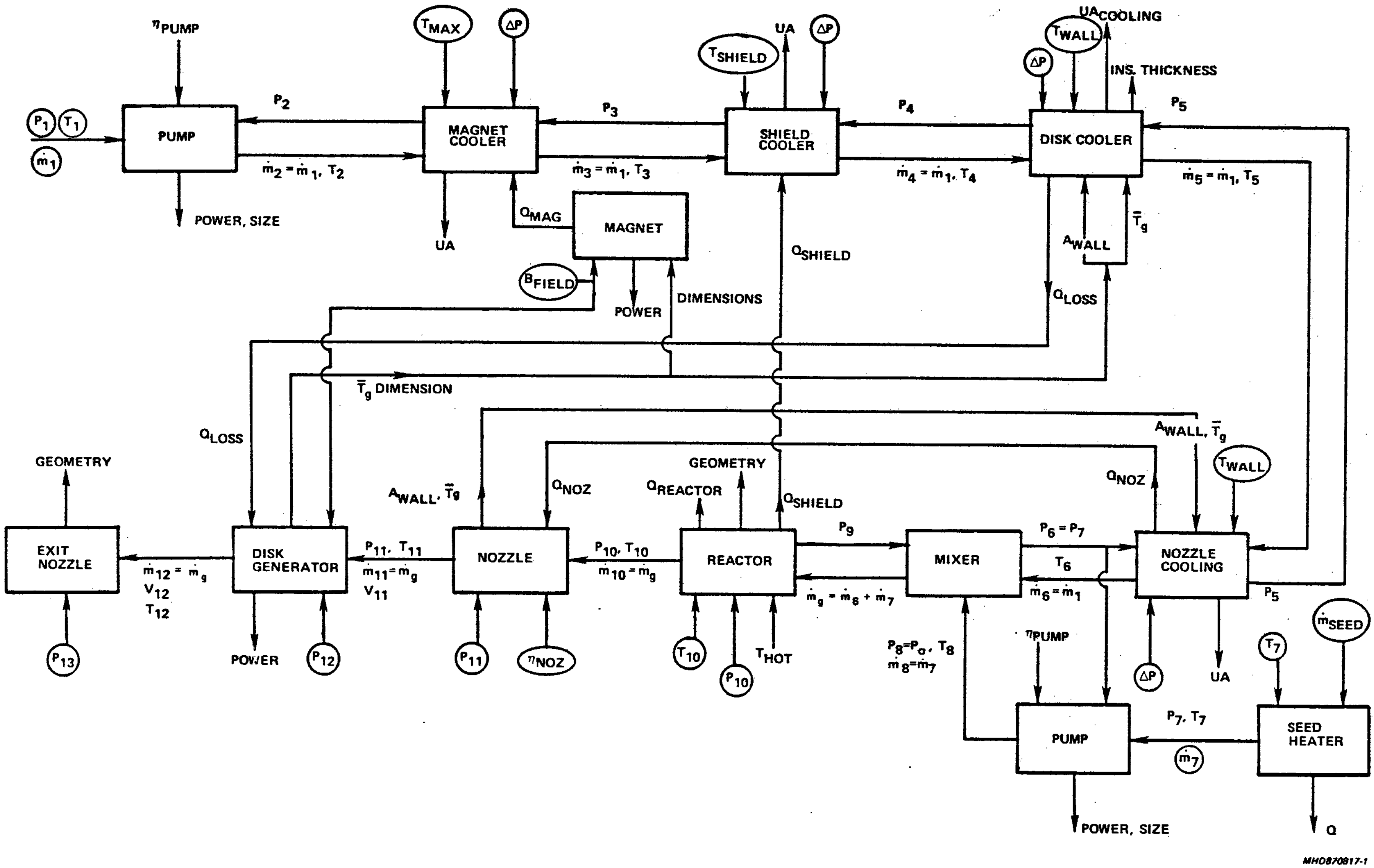


Figure 3-33. SPA Code/System Element Component Interfacings

model than desired for a system code. An early systematic appraisal in Task 1 of the overall system performance of the nuclear powered disk MHD space power system showed that a relatively sophisticated disk MHD generator model was required to establish its potential. Therefore, the system disk generator model found satisfactory for previous studies[3-8] was extensively modified. The need for this revision was found in the validating process of comparing the SPA disk generator calculation results with the results of the empirically verified Tokyo Institute of Technology calculations. After modifications, these two models agreed well as seen in Figure 3-34. The system models of the nuclear heat source and magnet system were much simpler.

Certain parameters involve constraints that must be recognized. Selection of reasonable levels of these parameters was necessary to obtain a calculated solution. An especially sensitive chosen variable combination was the β field, pressure and entry current loading factor. As discussed in Section 4.0, stable operation of the disk requires care in design of the entry loading and disk geometry for maximum power.[3-9] The analytical model recognizes the regime where power generation by the plasma is insufficient to meet current demands, and thus requires power absorption. This results in an unstable calculational condition with loading factor (K) levels above 1.0.

The imposed design condition also was a sensitive parameter that was constrained by the β field model. This, however, is a design factor that can be tailored as required in an actual disk which would not be subject to the system level disk model limitation.

The low sensitivity of the reactor heat source and structural elements of this system model and the compactness of the system permitted focus on the disk model and its sensitivity to the selected design conditions. Parameter ranges were selected for the reference case for studying the nonequilibrium ionization performance of the disk generator. These were restricted in depth for Task 1 parametric system analysis to principally the disk MHD generator design and operating parameters. The sensitivity level of the conversion system dry mass to disk performance and power is indicated in Figure 3-35. The required

Design Conditions - Tokyo Institute of Technology Disk MHD Generator

Common Inputs

Work Fluid	Helium + K
Thermal Input	1310 MW
Stagnation Pressure	4.0 Atm
Stagnation Temperature	2000 K
Mass Flow	126 kg/s
Seed Fraction	1×10^{-5}
Wall Temperature	600 K
Magnet Field Strength	6.8 -- 4.84 (T)
Magnet Radius	1.3 to 2.2 m
Inlet MACH No.	1.67
Radius - Inlet (Estimate)	0.7 m
Radius - Outlet (Estimate)	1.4 m

Performance Comparisons:	TIT	SPA
Enthalpy Extraction	35%	34.4%
Electron Temperature	5000 K	4500 K
Loading Factor	0.14	0.17
Outlet MACH No.	1.05	1.13
Radial Current	25.7 kA	24.1 kA
Hall Voltage	17.9 kV	18.6 kV
Effective Hall Parameter	10.5	12
Conductivity (Effective)	11.4 S/m	12 S/m
Isentropic Efficiency	76%	70%
Radius Inlet	0.7 m	0.78 m
Radius Outlet	1.4 m	1.24 m
Heat Loss	6.15 MW	13 MW

Figure 3-34. SPA Disk MHD Calculation Comparison with TIT Disk MHD Calculation

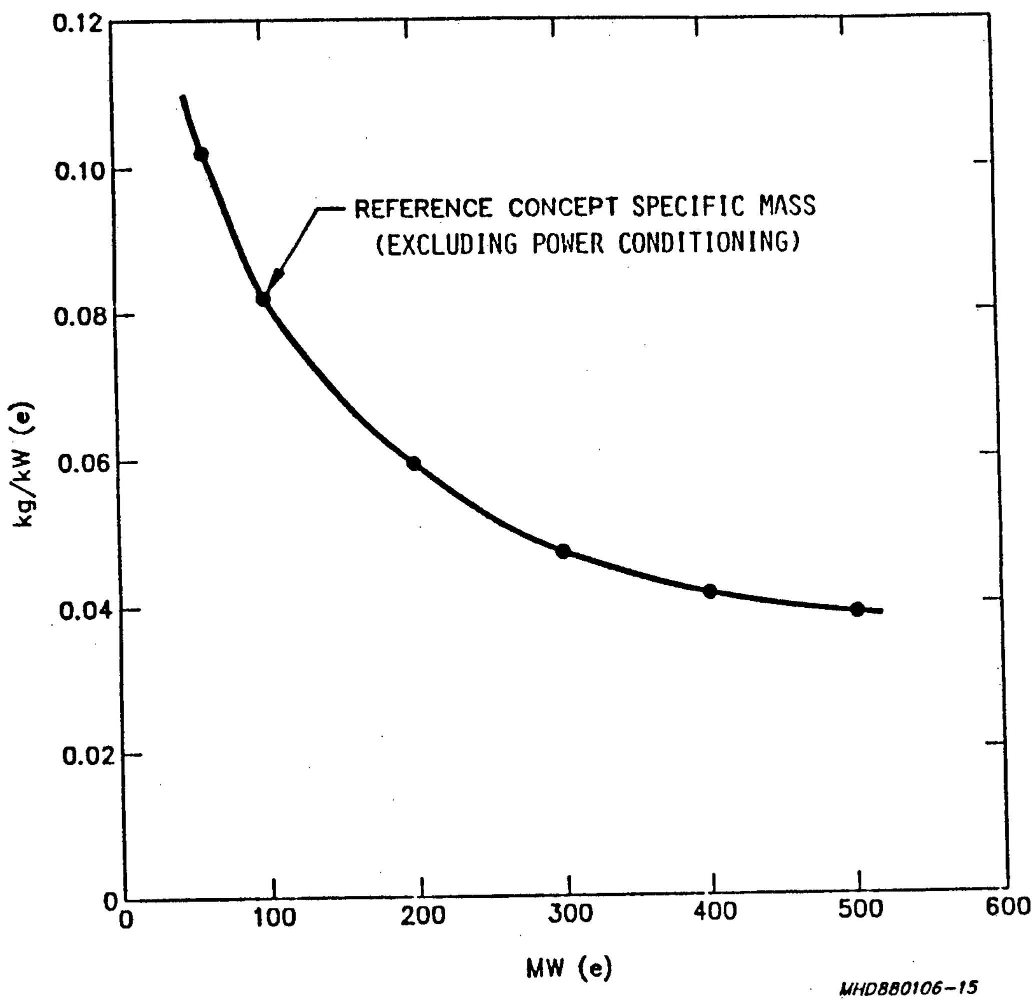


Figure 3-35. Power System Dry Mass Trend

hydrogen inventory impact due to energy extraction affects the system mass much more significantly than the disk generator mass. The reactor mass is essentially constant for power requirements to over 300 MW_e (NDR design level up to 600 MW thermal). The low hydrogen inventory mass of the reference disk generator system and excellent scalability to higher power levels give the system a significant advantage when more power is needed.

Assessment of the low sensitivities of the reactor heat source subsystem, hydrogen coolant subsystem, cesium seed subsystem and power system arrangement size and mass algorithms showed that the contribution of the disk and magnet mass scaling relations, even though attractive, predominated over the remaining system elements.

Disk MHD design and operating condition sensitivities and SPA model limitations for the system parametric studies conducted did not permit establishing the "best design" in this task. Obvious improvements in performance can be obtained with exercising a more detailed disk model in Task 2. However, the model studied did provide the necessary design guidance for assessing the system, and thus could be used to indicate the system performance potential.

Pertinent results of exercising the SPA disk MHD model are observed in the relationships noted from sensitivity studies. Figure 3-36 shows the cases identified early in the study for evaluation. It was found that loading in two sections of the generator inside the magnet radius, coupled with significant reductions in seed level, permitted good performance with realistic geometries.

After arriving at a satisfactory reference design, additional parametric studies were carried out to evaluate the impact of design parameters on the generator performance.

Figure 3-37 illustrates the impact of singular variable changes in generator design parameters on the performance. For the reference case, 16.5 MJ/kg of plasma energy was extracted from the inner two loading sections, with the

Case	J/J_s	$T_o(K)$	$P_o(Atm)$	Inlet Mach No.	C_s(mole fract.)	$B_o(T)$	Parameter Inputs for Case Variation
1	0.66	2900°	19	2.33	*	4.0	1.5×10^{-4} *1.0×10^{-4} 3.1×10^{-4}
2	0.6				1.5×10^{-4}		
3	0.56						
4	0.48						
5	0.2						
6	0.6				1.0×10^{-4}		
7	0.6				3.1×10^{-4}		
8	0.6		20.9		1.5×10^{-4}	4.4	B_o, P_o
9	0.6		17.1			3.6	
10	0.6	2600	19			4.0	J/J_s
11	0.5	2600	19			4.0	
12	0.66	2900	*	2.5		4.0	1.3 atm Calc. P_o
13	0.6						
14	0.56						*
15	0.48						
16	0.2						

NOTE: 1) Mass flow of hydrogen: 4.4 kg/sec, all cases.

2) Constant static temperature mode of operation: $dt/dr = 0$

3) If $\omega\gamma = 14$ or greater, then: $dp/dr = 0$

4) $\frac{P_o}{P} = [1 + \frac{\gamma-1}{2} M^2] \frac{\gamma}{\gamma} - 1$ $\gamma = 1.35$ for 1 atm @ 1500 K

Figure 3-36. Parametric Studies for MHD Disk Generator Characterization

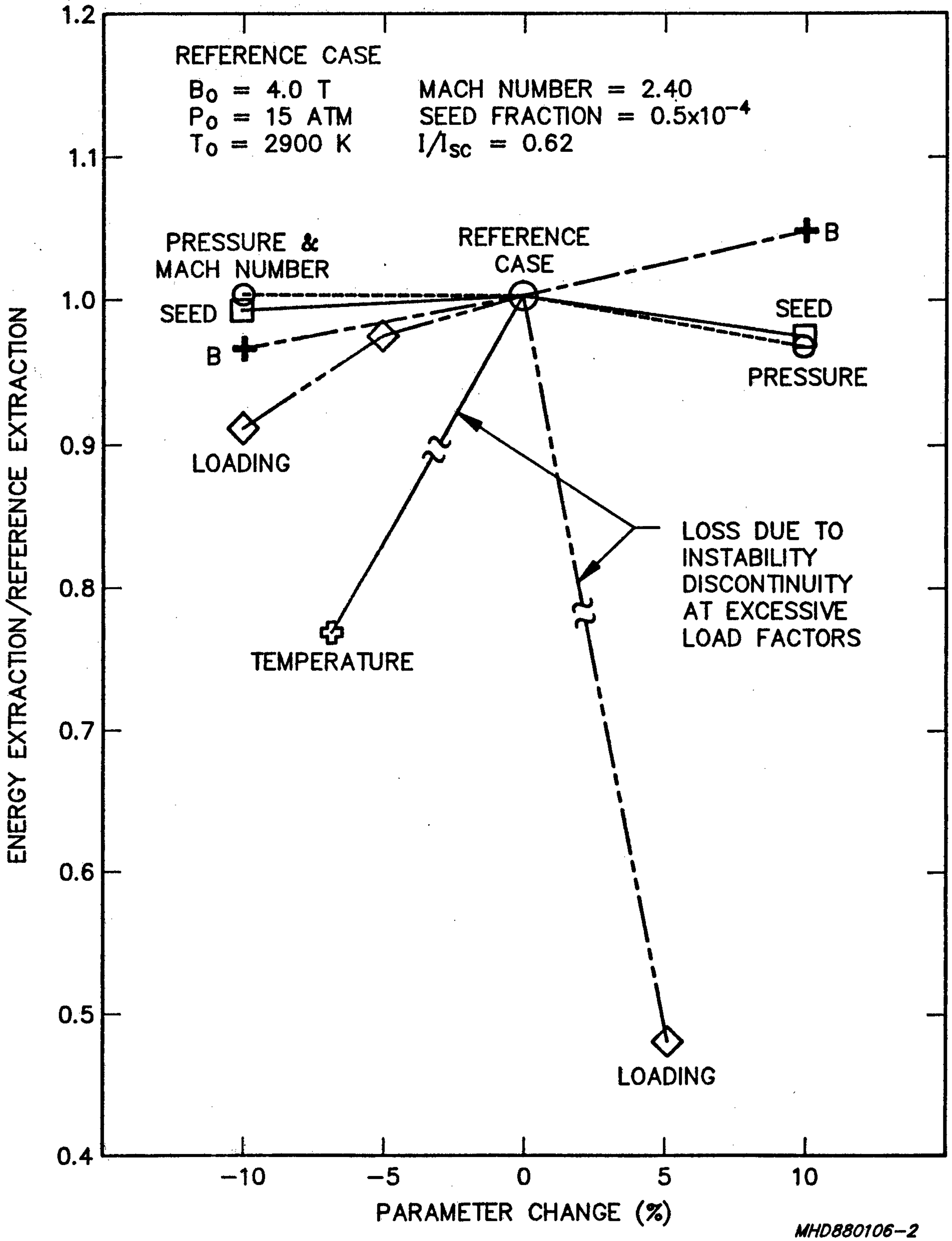


Figure 3-37. Sensitivity of Generator Performance to Selected Variables

remaining 3.5 MJ/kg extracted in the reversed field outer third section of the generator (outside the magnet radius). Calculations were changed in one of the variables, all the remaining parameters held constant.

The high sensitivity of field strength on the mass and energy required for the magnet resulted in the selection of a 4 T field strength for the reference design. Increasing the magnetic field yields an increase in performance, but a 10% change in field only increased the energy extraction by 5%.

The disk extraction performance is relatively insensitive to operating pressure and the reference seed concentration level of 0.5×10^{-4} mole fraction of cesium. Slightly lower seed or pressure levels will have little or no impact on performance, while increasing the the seed or pressure levels only tends to reduce performance slightly, all other parameters unchanged.

The current loading represents a critical parameter for establishing stable performance of the generator. For a Hall machine, in general, increasing the current loading increases the performance of the machine, as can be seen by the trend between -10% loading and the reference loading level. This generator, however, depends on nonequilibrium heating of the electrons to obtain ionization of the seed. The energy for this heating is extracted from the electrical dissipation in the plasma, as discussed in Section 3.2. With increased loading, this dissipation is reduced, and at a critical level, insufficient energy is available locally to sustain the required electron heating, and the performance of the generator drops sharply. In Figure 3-36 the critical load appears to occur with a ~ 5% increase above reference. Critical loading is a strong function of the selected design parameters for the generator, including the stagnation temperature. With a reduction of stagnation temperature from 2900 K to 2700 K, the reference loading factor of 0.62 is excessive, resulting in a calculated instability.

With the reference design conditions, reducing the inlet Mach number by 10% produced nearly the same effect as reducing the stagnation pressure by 10%;

less than a half percent increase in energy extraction. Operation with a low inlet Mach number, however, introduced problems with maintaining adequate electron heating along the generator radius.

In addition to the impact on performance, variations in the selected design parameters impacted the geometry of the generator. Figure 3-38 illustrates the impact of these parameters simply varied on the inner disk exit radius (geometry) of the generator. The inlet radius of 0.18 m was held constant for the study. With the exception of the loading and Mach number, the disk radius is a weak function of variations in the design parameters.

The largest impact on over-all system mass is the disk energy extraction performance factor, since the mass of hydrogen and seed required is nearly inversely proportional to the energy extraction. For the parameters examined, with the exception of the loading factor and the stagnation temperature, the impact on total system mass of these variances appears to be negligible.

This study has shown a need to design the field distribution that would define a more attractive geometry and higher extraction than our simplified B field model permitted. The disk design and, hence, overall system was not therefore optimized even with our enhanced SPA system model.

Selection of system design conditions with allocation of performance, size and mass targets for each principal element is usually accomplished after considering trade-off effects of a number of factors other than performance and initial equipment costs such as overall system size, mass, launch and economical impacts, operational margins, process requirements, etc. The principal consideration addressed here has been the disk MHD generator energy extraction since system size, launch mass and costs are highly leveraged to this parameter. Sensitivities related to control and operating envelope have also been investigated based on constraints and conditions that have been developed in previous studies and experiments.[3-10],[3-11],[3-12]

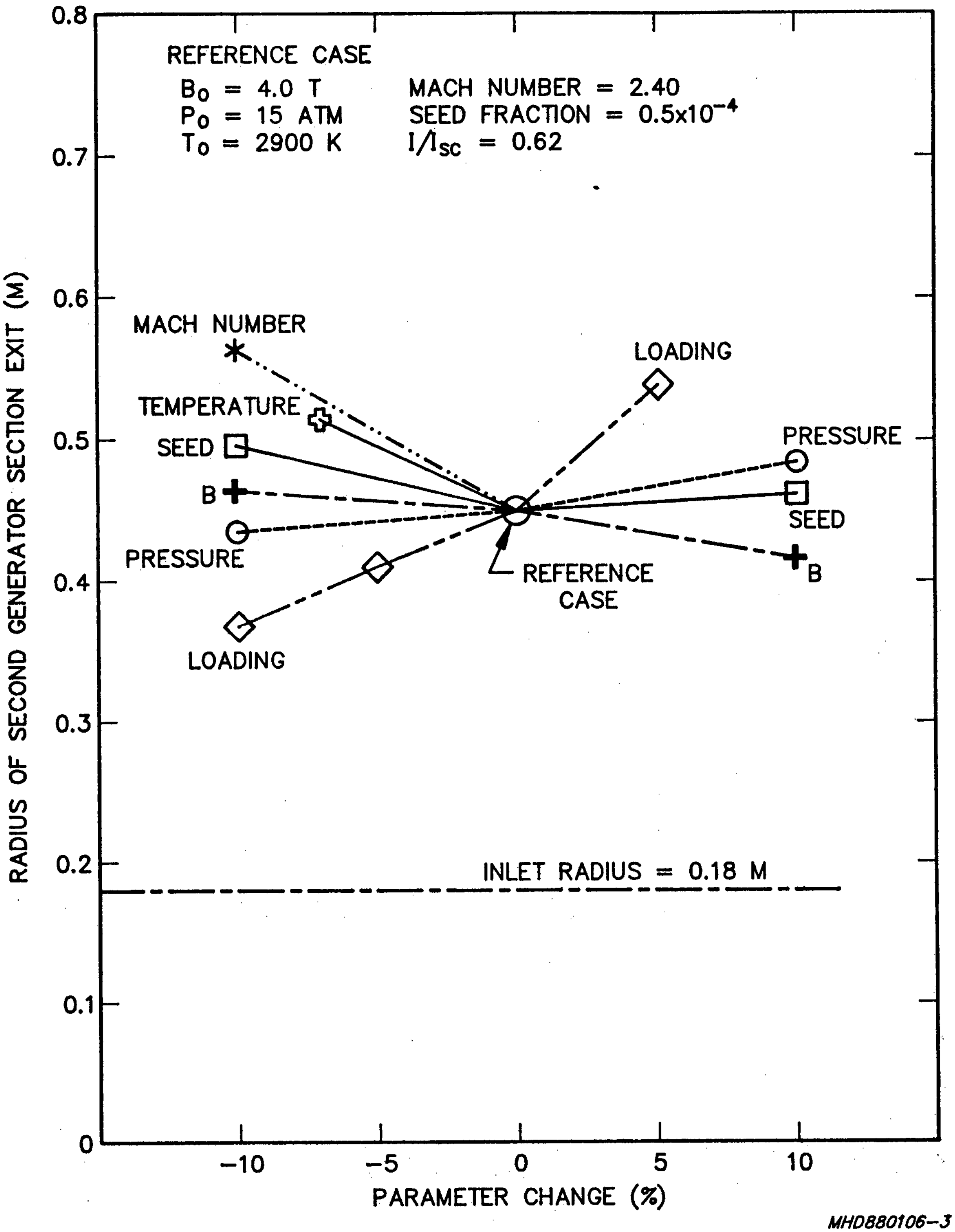


Figure 3-38. Sensitivity of Generator Geometry to Selected Variables

3.3 Operational Characteristics

STARTUP AND SHUTDOWN

The MMW/MHD power system has four operating modes: standby or station-keeping, ready, burst and test. In the standby mode power is required from an external source to maintain the MMW/MHD power system components in an acceptable temperature range, provide communications, and to maintain all MMW/MHD power system components in a state of operational readiness for transition to the ready mode.

As the generic NPB space platform is transitioned from the station-keeping or standby mode to the ready mode, the master control sequentially activates systems/components until the MMW/MHD power system is at the 25% power ready mode, and the NPB is ready to produce the beam. This transition occurs in less than 90 s. The ready mode power (25 MW_e) is used to drive controllers, cooling pumps, beam steering magnets, and ancillary systems which must be fully operational and verified before the NPB beam is turned on. Once in this ready mode, the NPB and the MMW/MHD power system are capable of ramping up to the full power burst mode in less than 1 s. In the burst mode, most of the full power output is used to drive the NPB beam.

Full power burst mode tests will be conducted twice a year to assure the performance capability of the complete system. For this generic NPB space platform design, 4 to 5 s of full power testing is required for system calibration and to assure that the NPB space platform and power system are in the necessary state of readiness.

After full power burst mode operation, the master control terminates NPB operation, ramps in the control drums to shut down the reactor, and shuts off the cesium seed flow. Then the hydrogen coolant flow is ramped down over a period of several seconds until the reactor temperature is reduced to approximately 700 K. At that point, the supply tank valve is closed to shut off hydrogen flow.

The complete load profile required for the MMW/MHD power system from initial startup, through test cycles, and through a battle period is illustrated in Figure 3-3.

A more complete description of the MMW/MHD power system operating modes is presented in the following paragraphs.

STARTUP PREPARATIONS

Startup is accomplished following in-orbit assembly of the MMW/MHD power system on the NPB space platform and after checkout of the system. The time required for assembly and checkout has not been specifically determined and could range from minutes to hours depending upon the final configuration of the space platform. After checkout, the cold reactor MMW/MHD power system will be ready for transition to the standby operating mode.

STANDBY MODE

In the standby mode the power consumed by the MMW/MHD power system is dominated by the refrigeration requirement to minimize the hydrogen working fluid boil-off, and to keep the MHD magnet cold and ready for rapid transition to the ready mode. The estimated peak power requirement during the standby mode for the power system is 50 kW, and the estimated average power is 30 kW. This standby power will be supplied by another system on the space platform such as a solar or an SP-100 nuclear power subsystem. After initial assembly and checkout, it is assumed that the MMW/MHD power system remains in the standby mode throughout the ten year lifetime, except when operating in the ready, test or burst modes.

READY MODE

The ready mode is an intermediate state in the transition from the standby mode to the burst mode. The ready mode is necessitated by the requirements to prepare the NPB for full power test modes or the burst battle mode and involves the startup of pumps and the conditioning of system components. Compared to the time allowed for transition from the standby to burst mode (less than 100 s), the actual operating time in the intermediate ready mode is 2 to 3 s. This ready mode pause is due only to NPB requirements and is not necessary for the MMW/MHD power system transition to burst power.

BURST/TEST MODES

Operationally, the burst and full power test modes and the transitions involved are the same. However, while the full power test modes of 4 to 5 s in duration are necessary every 6 months, it is assumed that a full power battle burst mode will take place only once. The tests conducted once every 6 months will demonstrate that the NPB space platform and the MMW/MHD power system are functioning properly. The first time that the checkout/calibration/boresight is conducted after the reactor has been started will be for the purpose of checking the alignment of the system, determining whether the assembly was successful, and whether the NPB is aimed at the target as seen by the sighting sensor. This would entail conducting one checkout cycle, examining the output data, and then making adjustments and rerunning the cycle as shown in Figure 3-3. All checkout/calibration/boresight runs are to be done at full power to verify that the beam is accurate and up to full power.

LOAD PROFILE

After the power system is assembled on the space platform and checkout has occurred, the standby mode would first be established through the use of the refrigeration equipment to cool down and condition the NPB equipment and the MHD magnet. Once the standby mode has been achieved, and all components of the platform and MMW/MHD power system are verified operational, charging of the power system magnet would be initiated along with ramping the nuclear reactor control drums out to a position to put the reactor on a 4 to 5 s neutronic period. The hydrogen supply tank valve will also be opened to initiate the transition to the 25 MW_e ready mode. Startup of the NDR power system reactor will duplicate the nuclear rocket engine startups that have been demonstrated in the NERVA test program. Typical character- istics of a nuclear rocket engine reactor startup are shown in Figure 3-39. While the power system pumps and piping are designed for low temperature operation, some chill-down is necessary during the transition to the ready mode at 25 MW_e.

At first, the pump tends to vaporize the fluid until sufficient fluid passes through it to chill the pump down to cryogenic conditions. The piping also tends to be a choke point. Therefore, a certain amount of cryogenic fluid must be passed through the system to remove the stored heat in the pumps and lines. Once this is accomplished, the pump can be started and will operate normally. During this time period, the reactor can be brought up to a low-power level. Once appreciable temperature rise is sensed in the reactor core, the reactor can be switched to closed-loop temperature control. When appreciable power has been achieved and the pump is running, the reactor power ramp up to the ready mode (full reactor power, 25 MW_e net output power) can be completed. Experience with the NRX/EST and XE' nuclear rocket engine tests during the NERVA/ROVER Program demonstrated that this control method is predictable and safe.

From the 25 MW_e level (Ready mode), the power system can be raised to the 100 MW_e power level in a fraction of a second, but the NPB load requires the input power first to be held at the 25 MW_e ready mode level for 2 to 3 s to allow the accelerator to clear the impurities from the stream. All of the transition times are compatible with the operation of the reactor and power system.

After burst mode operation, the reactor control drums would be ramped in to shut down the reactor, and cesium seed flow would be shut off. Hydrogen coolant flow would be ramped down over a period of several seconds and then terminated when the reactor temperature is reduced to 700 K.

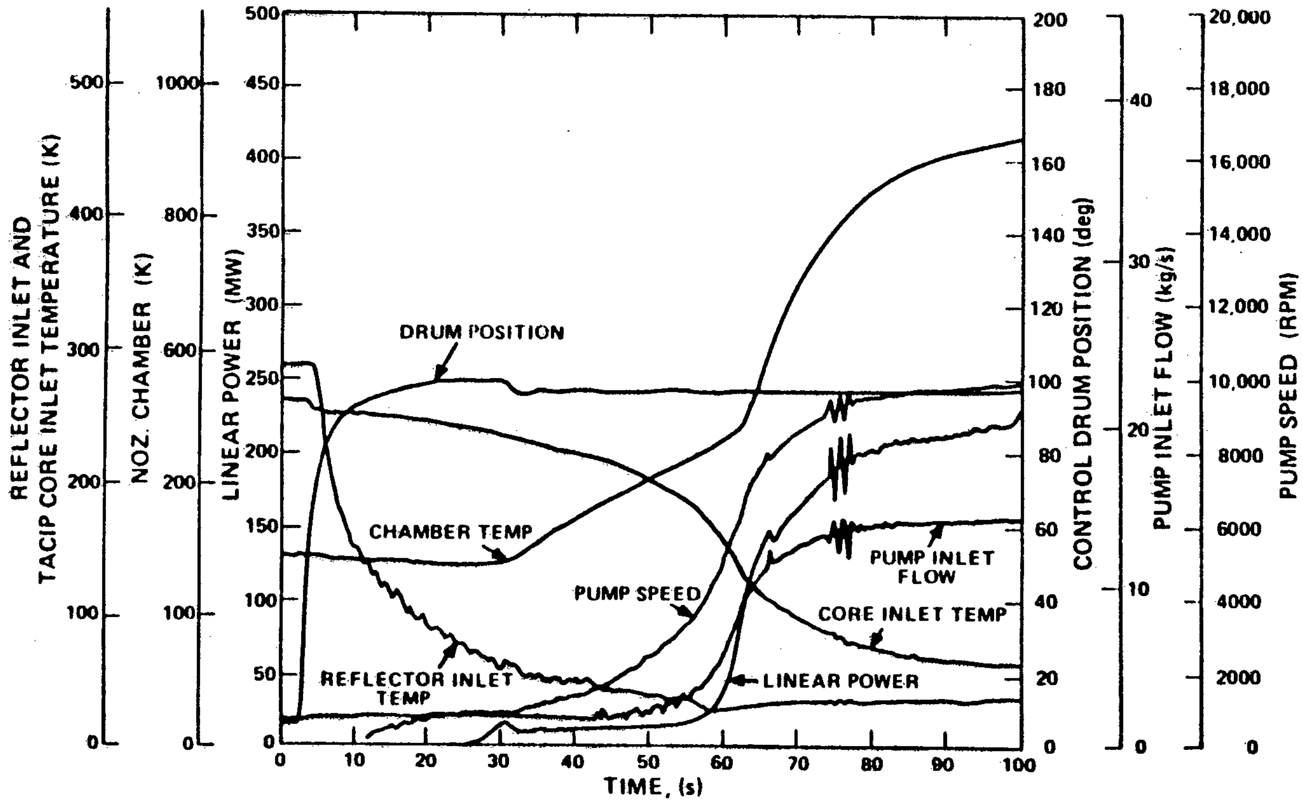


Figure 3-39. Typical Characteristics of the Nuclear Rocket Engine Startup

3.4 Spacecraft Integration

To develop the MMW/MHD nuclear reactor power system, it is necessary to select construction concepts and materials that are compatible with the Space Transportation System (STS) that launches the power system into orbit. Since the NPB system at this power level is too large to be launched with all of its subsystems aboard, the MMW/MHD power system will have to be launched separately. Assembly in low-Earth orbit then will be required for the NPB operational spacecraft(s).

If the power system is assembled on Earth as an operating unit with the hydrogen tank filled with cryogenic hydrogen, the shuttle booster cannot be used as the launch vehicle because cryogenics are prohibited in shuttle payloads.

The Scenarios for launching the power system and assembling it with the NPB in orbit are:

- Assemble the MMW/MHD nuclear reactor power system on Earth with cryogenic hydrogen in the tank.

  Candidate Launch Vehicles: Any unmanned booster with adequate payload capacity, e.g., advanced Titan, or a heavy lift booster.

- Assemble the MMW/MHD Nuclear reactor power system with its hydrogen tank empty. The tank will be filled in orbit after the power system is assembled on the NPB spacecraft.

  Candidate Launch Vehicles: The shuttle orbiter or any unmanned booster with adequate payload capacity.

- Assemble the MMW/MHD nuclear reactor power system without the hydrogen tank. After assembly in orbit on the NPB spacecraft, connect the hydrogen lines to the cryogenic hydrogen system on the NPB spacecraft.

Candidate Launch Vehicles: The shuttle orbiter or any unmanned booster with adequate payload capacity.

Assembling the MMW/MHD power system on the NPB spacecraft requires a fine control propulsion unit to maneuver the power system so that mounting appendages may be aligned for fastening in place. The launch vehicles do not have the capability to perform this accurate maneuvering for the assembly process. Thus, it will be necessary to use an Orbital Maneuvering Vehicle (OMV), Figure 3-40, that is presently in development. The OMV is pancake shaped, is about 1 m thick, and is designed to fit in the 4.6 m diameter of the shuttle bay. All propulsion and sensing for maneuvering and docking a playload can be accomplished with the OMV and its kit of remote sensors. Since the OMV is reusable, it does not have to be attached permanently to its load and can be used for assembling any number of NPB spacecrafts and their subsystems.

The OMV can be launched with the MMW/MHD power system in the shuttle or on an unmanned booster or it can be attached to the power system in orbit during the assembly process. It can then be removed when assembly is completed.

Figure 3-41 shows a MMW/MHD nuclear reactor power system mounted on an unmanned launch booster and containing an OMV and a remote sensing unit for providing the fine maneuvering for mounting the power unit on the NPB spacecraft. Figure 3-42 shows a sketch of a NPB spacecraft with the MMW/MHD nuclear electrical power system for the burst power. Figure 3-43 shows a typical installation of the Inertial Upper Stage (IUS) with a Galileo spacecraft installed in the shuttle orbiter bay. Since the MMW/MHD nuclear power system is about the same size and weight as the IUS, the installation of the MMW/MHD power system can be made similar to the IUS installation. The IUS has already been used to launch spacecraft, so the installation technology is established. Details remain to be designed for specific installation in the shuttle.

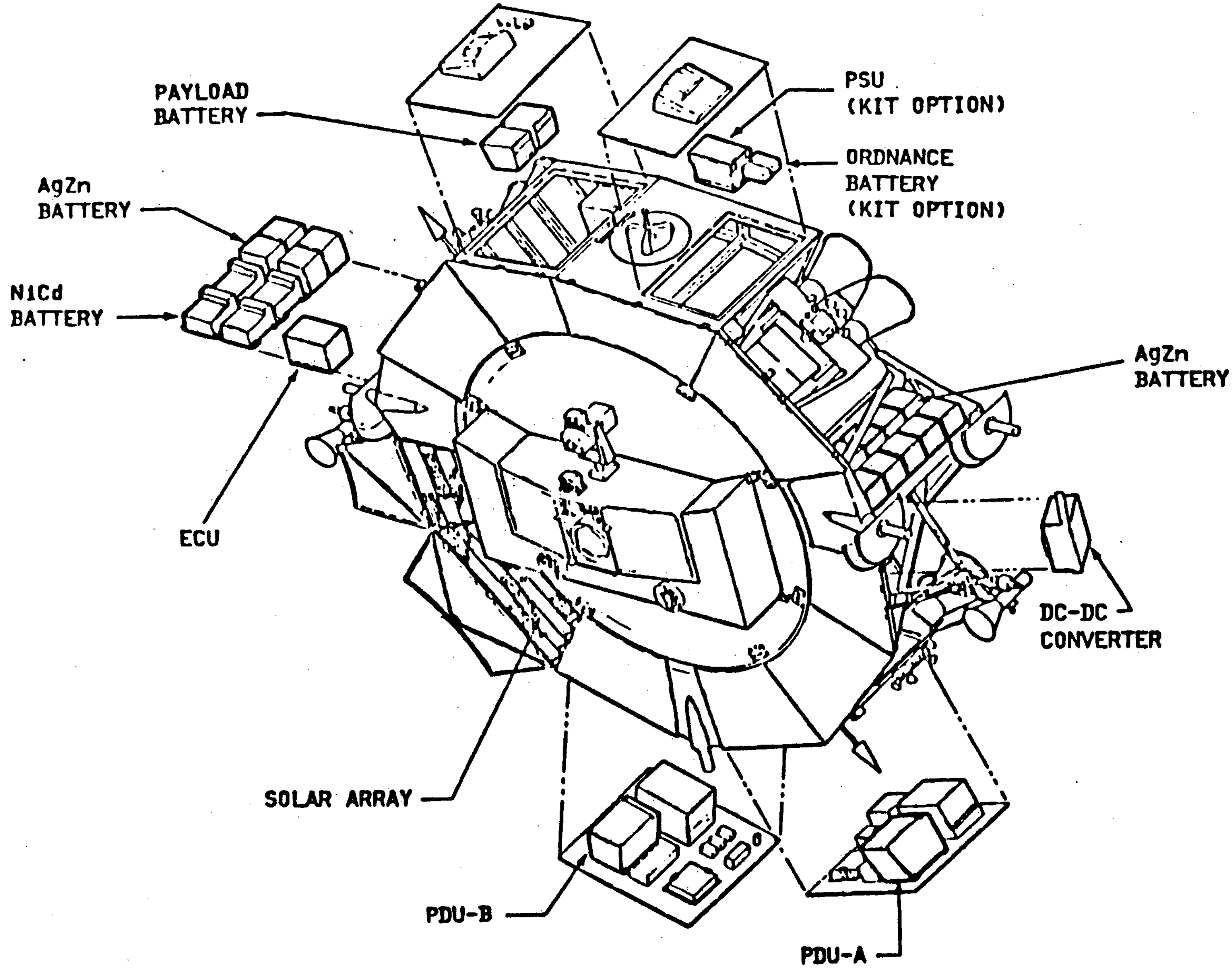


Figure 3-40. OMV Electrical Power Equipment

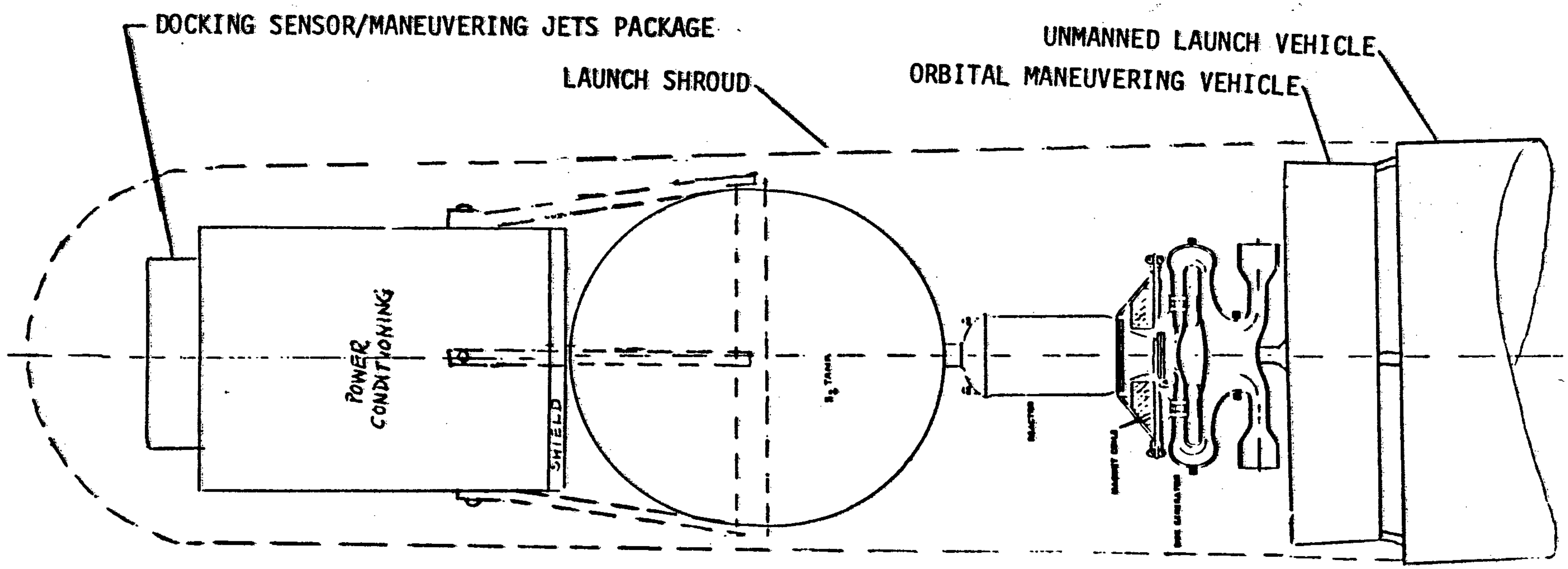


Figure 3-41. MMW/MHD Power System Typical Launch Configuration on an Unmanned Launch Vehicle. (Structural Supports not Shown.)

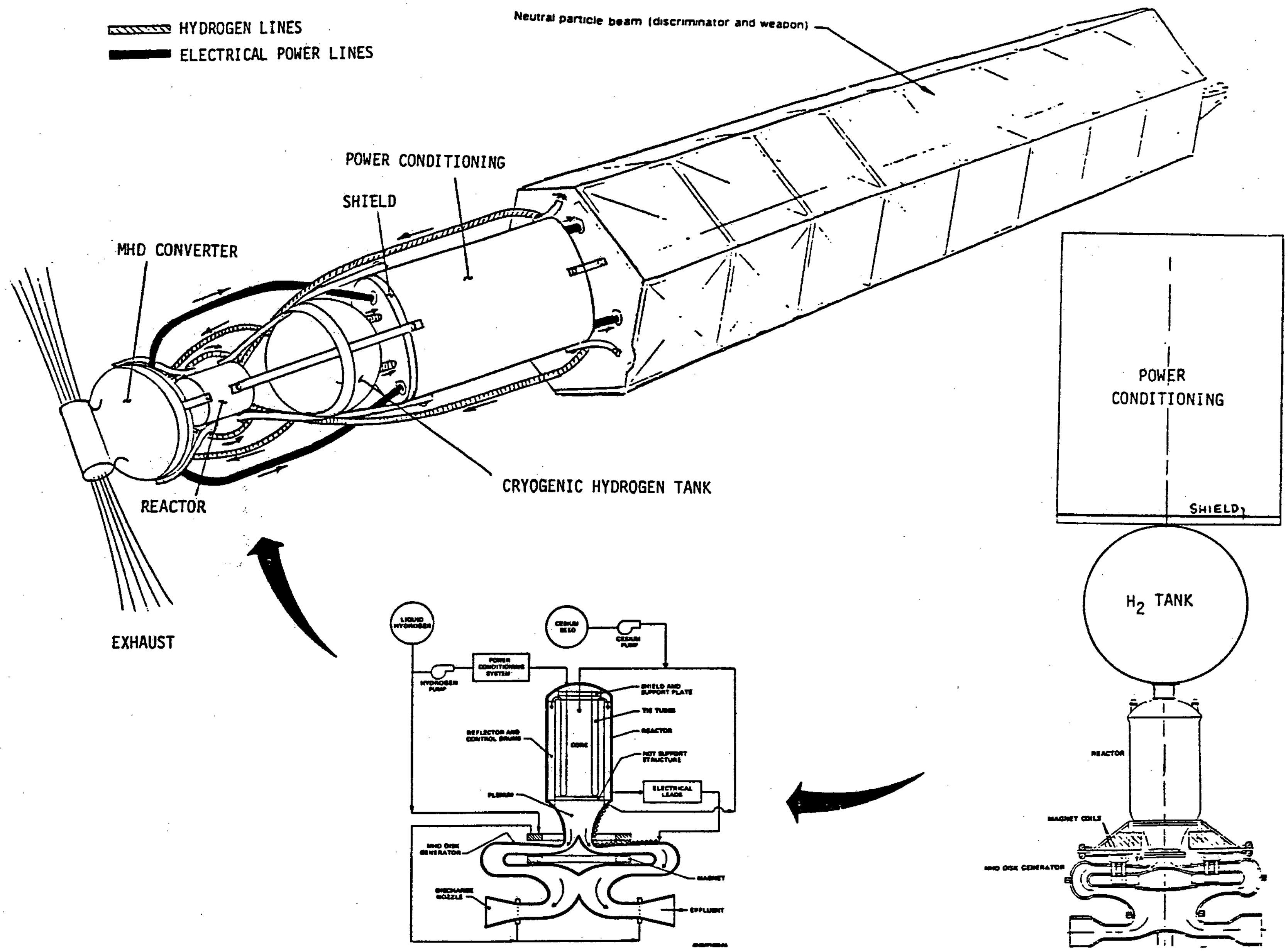


Figure 3-42. Perspective Sketch of Multimegawatt Space Nuclear Power Supply

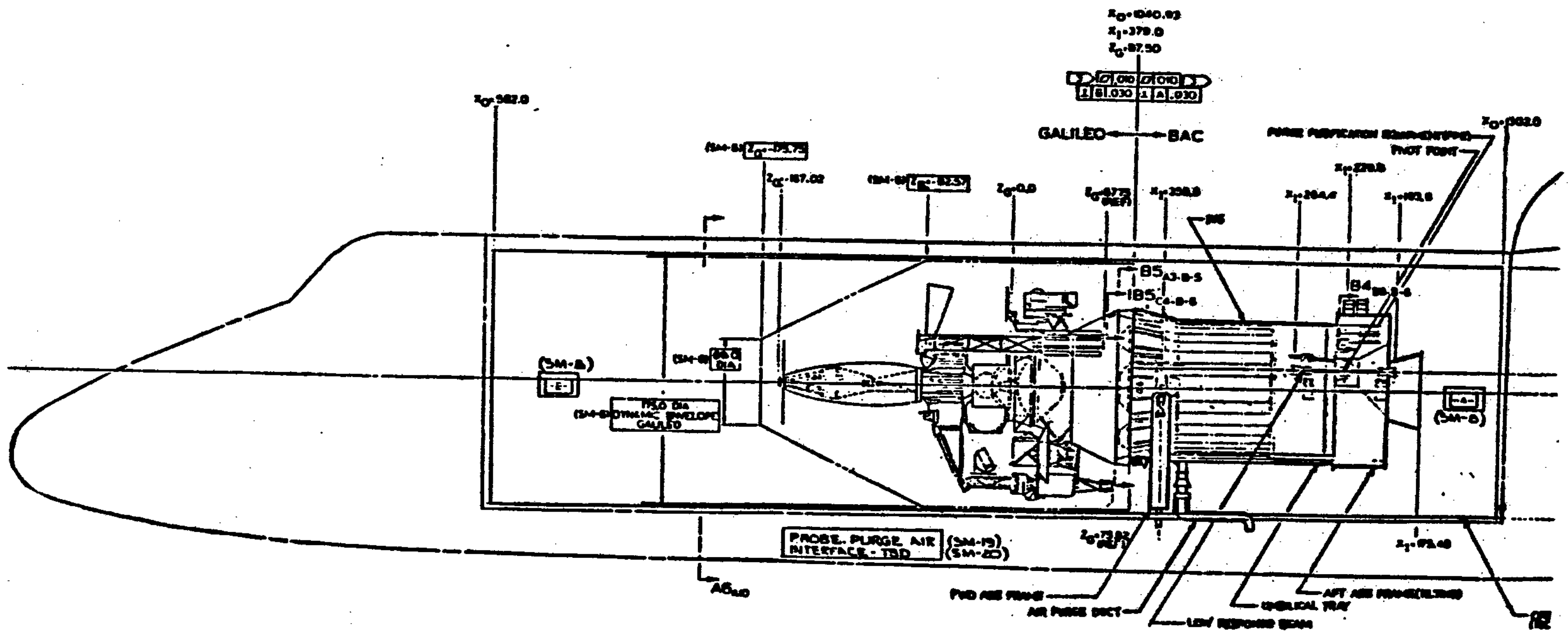


Figure 3-43. IUS Installation in Shuttle Bay

Requirements for any launch installation will include structural bracing, damping, and insulation against static thrust, shock loads due to stage separation or tank ejection, vibration, and temperature excursions for the following major components:

- Cryogenic hydrogen tank
- Cesium tank
- Nuclear reactor
- Plumbing, tubing, and pumps
- MHD converter and magnets
- Power system safety monitoring and control instrumentation
- Power conditioning equipment section
- Command and control receiving/transmitting subsystem

The installation must comply with the safety requirements for abort during launch and from orbit, so the design of the power system must provide separation joints at appropriate places on the components and on the launch installation supports and structure.

Unmanned launch vehicles are being developed to launch shuttle payloads when the shuttle cannot be used because of safety or schedules. The launch environment for the unmanned boosters will be no more severe than the launch environment of the shuttle so that the launch vehicles can be selected interchangeably as far as physical parameters are involved. Appendix C of the "Requirements Document" defines the parameters of the shuttle launch.

A battery-operated instrumentation, control, and monitoring power system will be required on the MMW/MHD power system for controlling the safety of the MMW/MHD power system and its controls. This auxiliary power system will be installed on the MMW/MHD power system so that monitoring power will be available continuously for operating the safety mechanisms in an emergency. When the power is available from a launch vehicle or from the NPB spacecraft, the monitoring auxiliary power system will be paralleled with the onboard power system to keep the battery fully charged. The auxiliary power system will remain with the nuclear power system at all times to insure safety.

RADIATION FROM THE NPB WEAPON

- Electromagnetic Interference (EMI): The EMI environment is undefined at present and cannot be estimated accurately. Plans are included in the NPB program to measure the EMI when the NPB hardware is being tested. Until the EMI environment is defined, MIL-STD-461C dated August 4, 1986 is to be used. Figure 3-44 shows the parts included in MIL-STD-461. The parts applicable to this program are 1, 3, and 9. These include the interference from the operation of the NPB, the radiation from the MMW/MHD power system, and the hostile environment caused by a weapon firing at the spacecraft - EMP, neutrons, thermal radiation.

- Nuclear Radiation: Neutron and gamma radiation from the NPB during operation is classified information since it involves weapon characteristics. Such information will have to be evaluated through appropriate channels. The nuclear environment caused by a nuclear weapon burst is defined partially in MIL-STD-461, and the remainder of the hostile environment caused by a nuclear weapon burst is classified and must be treated through other information channels with suitable classification.

COMMAND AND CONTROL

To keep the reactor safe under all conditions of launch, launch vehicle abort, in-orbit assembly and operation, maintenance, disposal, and in-orbit accident, a command and control subsystem must be installed on the MMW/MHD power system and must be provided with power from the auxiliary power system that powers the reactor safety monitoring and control instrumentation. The command and control subsystem includes a receiver, a transmitter, an antenna, signal processors, and switching to connect into the safety

PART 1	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnet Interference	**PART 6**	Requirements for Equipments and Subsystems Installed in Submarines
PART 2	Requirements for Equipment and Subsystems Installed Aboard Aircraft, Including Associated Ground Support Equipment	**PART 7**	Requirements for Ancillary of Support Equipments and Subsystems Installed in Noncritical Ground Areas
PART 3	Requirements for Equipment and Subsystems Aboard Spacecraft and Launch Vehicles, Including Associated Ground Support Equipment	**PART 8**	Requirements for Tactical and Special Purpose Vehicles and Engine Driven Equipment
PART 4	Requirements for Equipment and Subsystems Installed in Ground Facilities (Fixed and Mobile, Including Tracked and Wheeled Vehicles)	**PART 9**	Requirements for Engine Generators and Associated Components, Uninterruptible Power Sets (UPS) and Mobile Electric Power (MEP) Equipment Supplying Power to or Used in Critical Areas
PART 5	Requirements for Equipments and Subsystems Installed in Surface Ships	**PART 10**	Requirements for Commercial Electrical and Electromechanical Equipment

Figure 3-44. Breakdown of MIL-STD-461C Parts

monitoring and control subsystem. Information signals describing the status of the monitored parameters are to be processed and transmitted to the ground receiving station, the manned cockpit of the shuttle, and the manned control cabin of a spacecraft, as appropriate. Command signals from the ground station or the manned cabin are to be received and processed on the MMW/MHD power system to cause the control subsystem to react to the command. Figure 3-45 shows a schematic of the Command and Control subsystem integrated with the Instrumentation/Control subsystem for monitoring the MMW/MHD power system. Because of the safety requirements governing the use and operation of the nuclear reactor power systems, the Command and Control and the Instrumentation/Control subsystems and their associated Auxiliary Power subsystem will be made redundant to meet the reliability and safety requirements. Figure 3-45 does not show the redundancy.

Since the Command and Control subsystem is involved in the safety of the MMW/MHD power system, the subsystem must be made secure to jamming and interference. Thus, the subsystem must meet the requirements of MIL-STD-461C for EMI and the standard for secure communication (TEMPEST), NACSIM 5100.

INSTRUMENTATION AND CONTROL

A nuclear reactor electrical power system is controlled at all times to assure safety. In order to assure safety, complete instrumentation and monitoring equipment must be in place and must be in operation at all times so that the power system can be monitored. The power for the Instrumentation/Control subsystem must be independent of any vehicle power because monitoring must take place when the system is isolated from the spacecraft, such as during launch and in-space assembly. Thus, the Power subsystem for supplying the Instrumentation/Control subsystem will have an independent energy source, such as a rechargable battery. The power supply for the Instrumentation/Control subsystem as well as for the Command and Control subsystem will be reliable and independently powered, as shown in Figure 3-45.

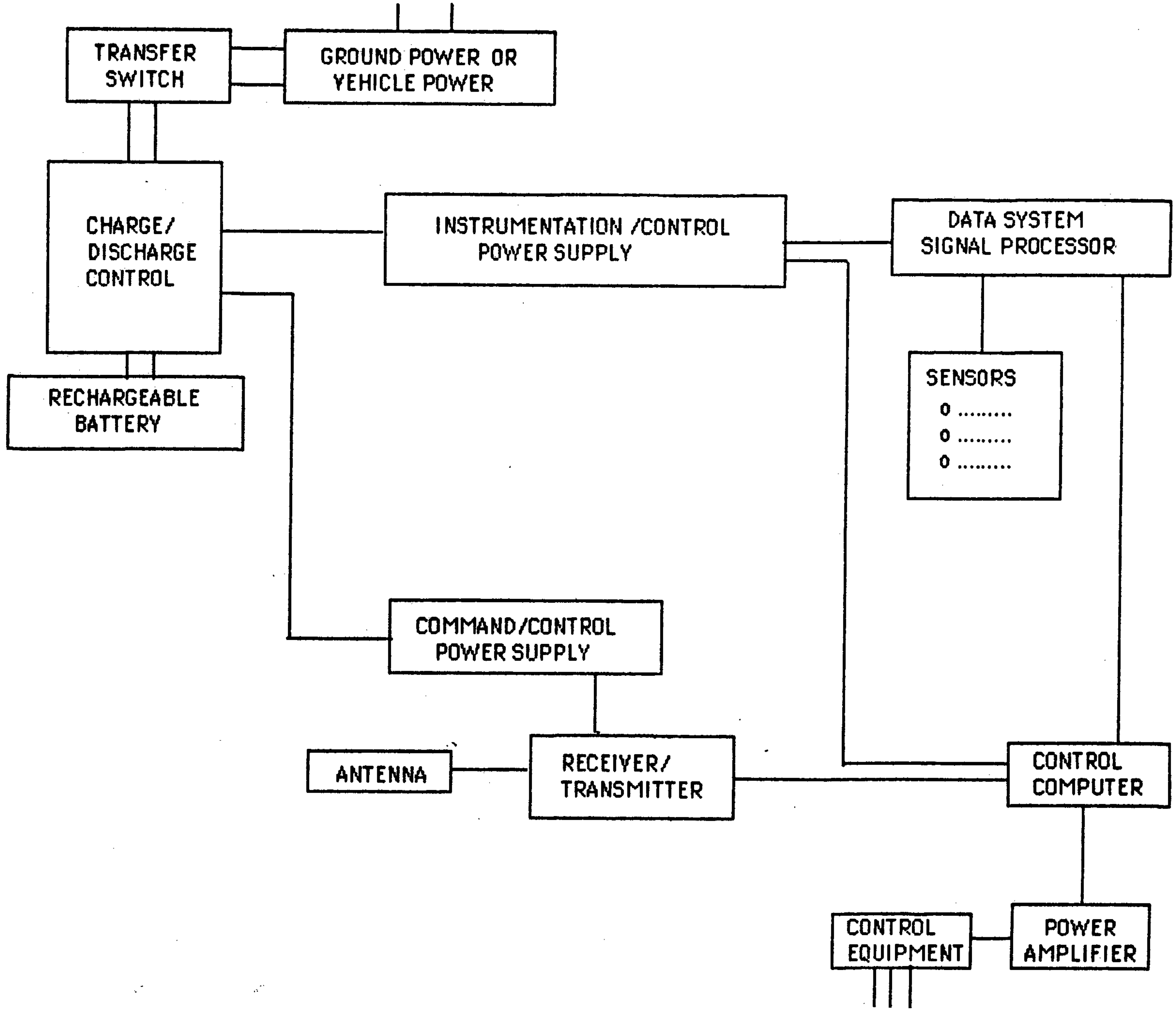


Figure 3-45. Auxiliary Power Subsystem Instrumentation/Control Subsystem Command/Control Subsystem

(Redundancy not Shown)

The measured parameters for monitoring will first be selected to satisfy the safety requirements for the reactor and the power system, and be integrated for the entire spacecraft. The established priority for the parameters measured is dependent upon the speed with which they change and their sensitivity related to safety. Sampling rates are thus determined for establishing the design of the Auxiliary Power, Instrumentation/Control, and Command and Control subsystems.

The relationship of the Instrumentation/Control subsystem to the Command and Control subsystem is that the Instrumentation/Control subsystem must provide the information about the parameters under surveillance; the Command and Control subsystem relays the information to a computer and to personnel monitoring the nuclear power system, and receives commands that are, in turn, sent to the Instrumentation/Control subsystem for any action required.

POWER CONDITIONING

To provide the required voltage, current, and frequency for the load, the output power of the MMW/MHD power system must be transformed by power conditioning equipment. If the load is distant from the output leads of the MHD converter, a transmission line may be required. The transmission line has to be operated at a sufficiently high voltage to minimize the line losses. Since the MHD converter output voltage is several kV and the specified requirement 100 kV, power conditioning is required between the MHD output and the load. The optimum condition would be when the MHD generator is placed close to the NPB load to minimize the losses in the power lines. The lines should be operated at the highest voltage, e.g., 100 kV, to lower the line current and thus lower the I^2R loss. For operating in space around Earth, consideration must be given to the effects of the Earth's plasma. The initiation of leakage current that leads to breakdown is dependent upon the altitude at which the spacecraft operates. Figure 3-46 shows the plot of the leakage initiation voltage versus altitude. A properly insulated system can be made to avoid the effect of the plasma.

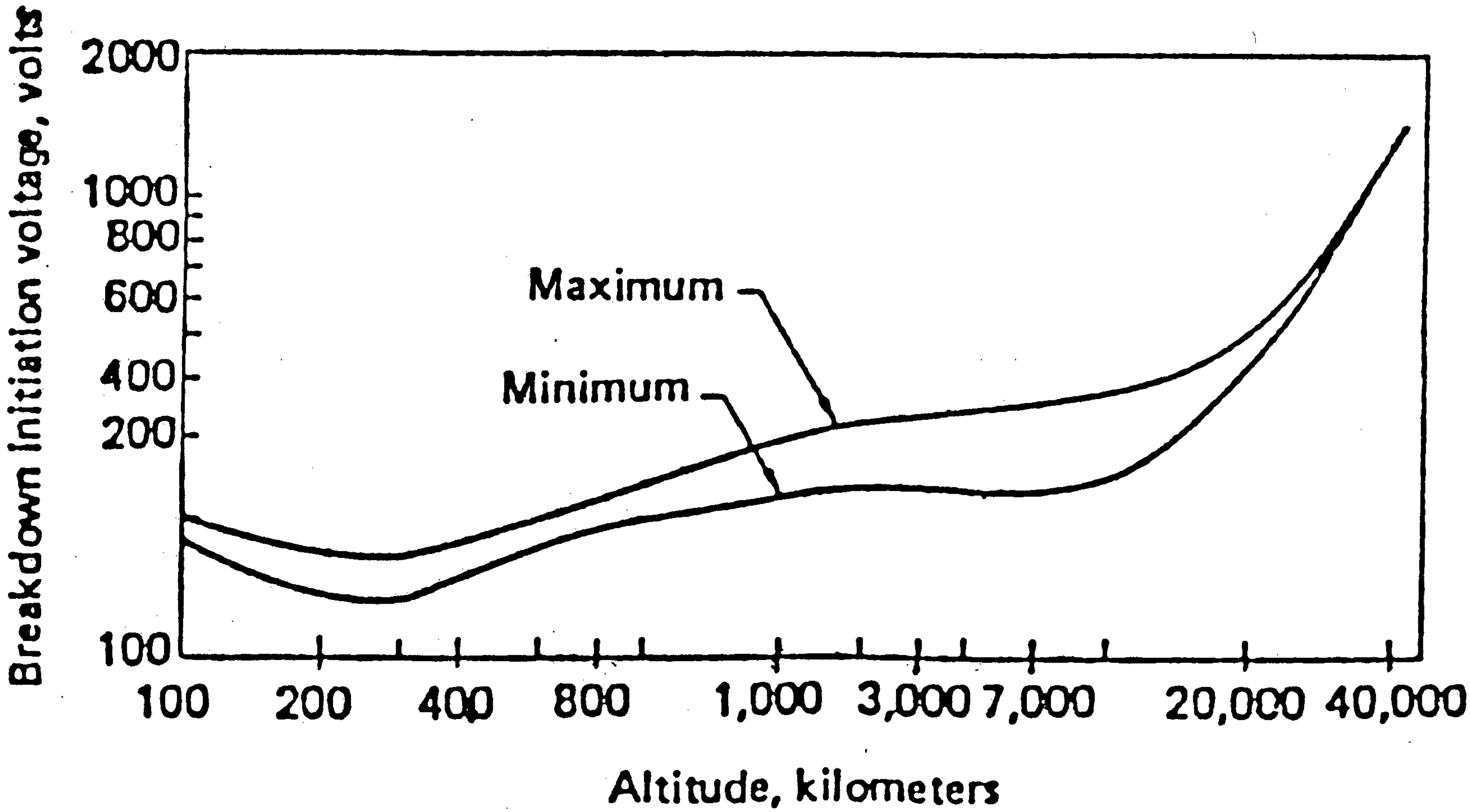


Figure 3-46. Corona Onset/Leakage/Breakdown Voltage vs. Altitude

Since the MMW/MHD power system only operates for short periods of time, the maximum being 500 s, insulation deterioration due to long operating time is not a factor. However, to protect the system from the plasma, the insulation must cover all terminals as well as the cables and bus bars that are exposed to the plasma. The coatings and insulation must be capable of surviving the space environment for the 10 year life of the spacecraft. The long term exposure can be significant for some materials even though the operating stresses occur for a short time only. To deter the plasma, there are several methods available, such as coaxial cable, running the cables/busses in metallic troughs that are properly grounded, and placing ground plane shielding around terminals and connections.

If the distance between the MHD generator and the load is great, the transmission line may enter into the system design concept. The power conditioning equipment will be comprised of converters, inverters, regulators, transformers, inductors, capacitors, and numerous semiconductors. Many of the components are sensitive to the nuclear and thermal radiation from the reactor and the electromagnetic effects of the MHD generator. Figure 3-47 shows the sensitivities of electronic components to the neutron and gamma radiation. It is desirable to have short power lines between the MHD generator and the power conditioning equipment because the high current leaving the generator will contribute to the power line losses. Converting to the higher voltage for the load should be done as close to the generator as possible. Some shielding may have to be added if optimization suggests moving the power conditioning close to the MMW/MHD reactor. When the installation design is being formulated, a tradeoff can be made between the mass of shielding, the mass of the umbilical structure, the mass of the cable/bus, and the losses in the power line.

Figure 3-48 shows the various combinations that may occur for conditioning the power to the load. Power conditioning equipment efficiencies are in the range of 80 to 95%. Since the 100 MW_e of load power is processed by the power conditioning equipment, 5 to 20% of the power is heat due to losses; this represents 5 to 20 megawatts of heat to be dissipated. Because the

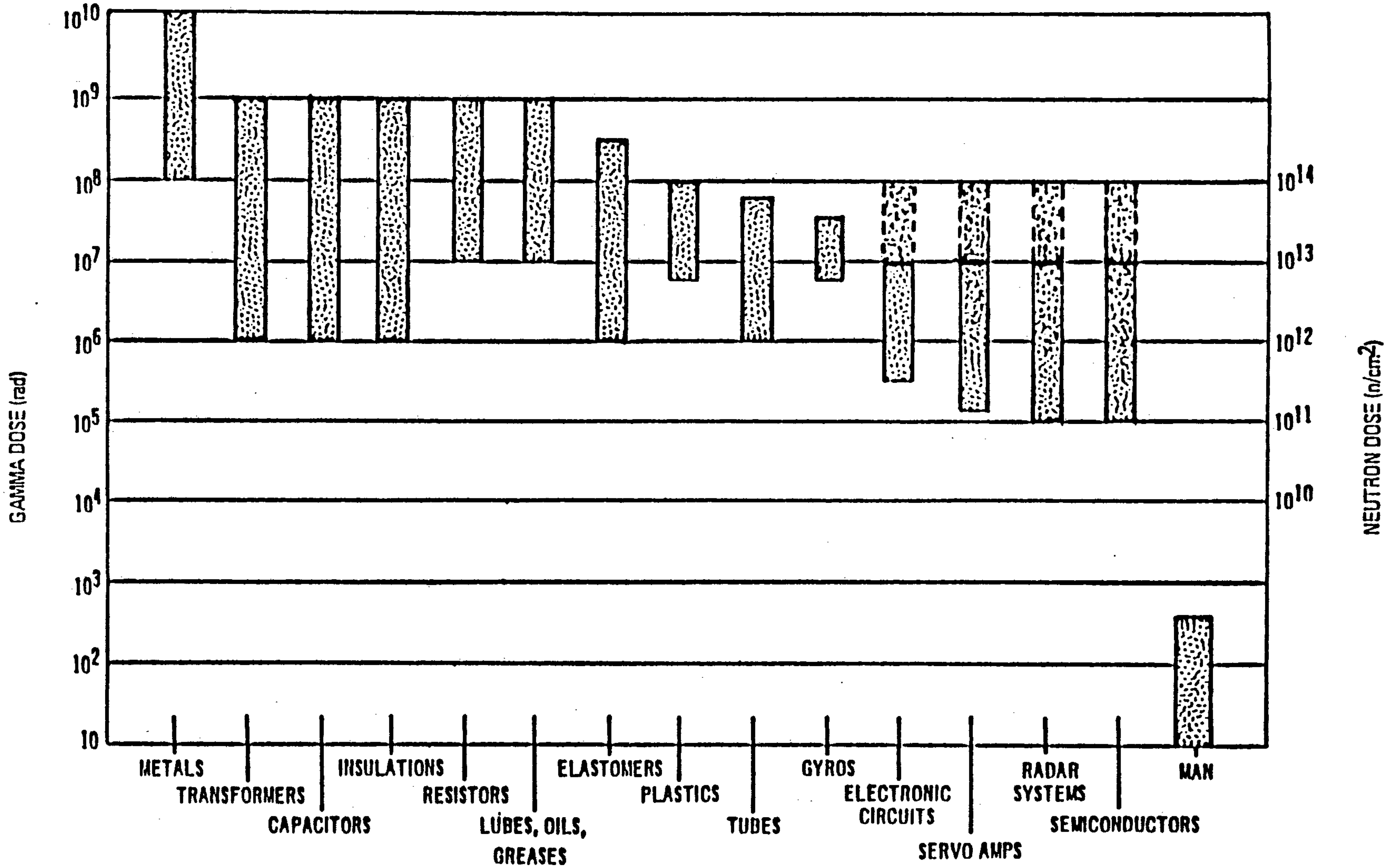


Figure 3-47. Radiation Damage Thresholds

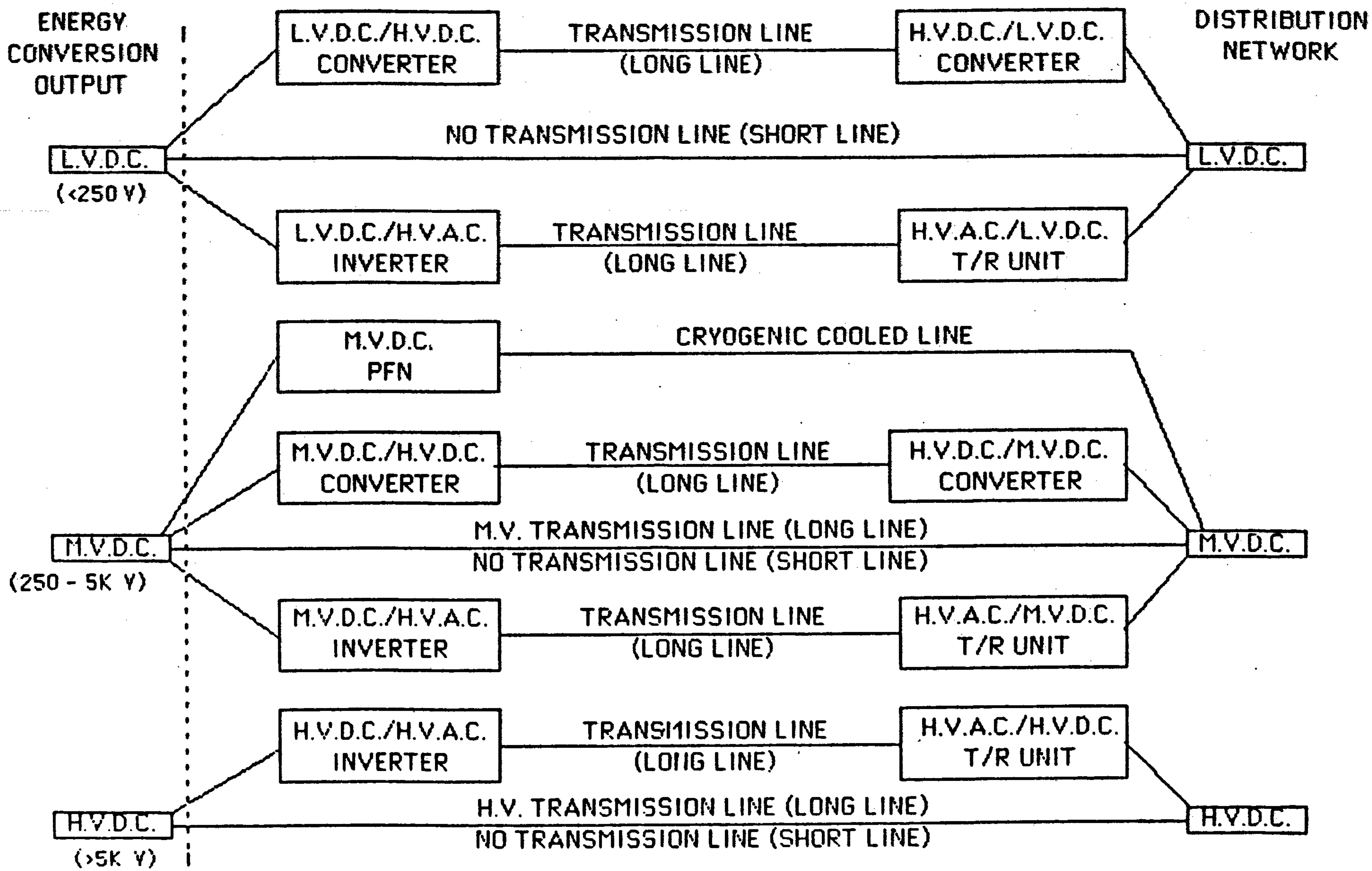


Figure 3-48. Power Conditioning and Distribution from DC Sources

power system will operate for 400 to 500 s at maximum power during an encounter, forced cooling must be used for the power conditioning equipment. The method of cooling is to pass the cryogenic hydrogen through the power conditioning and then through the reactor. Because of this flow path for the hydrogen, the placement of the hydrogen tank can be optimized to minimize the tubing line lengths. A tradeoff of designs of various hydrogen tank placements can be made. Each position of the tank will affect the parameters of shielding, mass, center of gravity of the system, complexity of connections, and structural support design for the launch installation. In addition, an abort safety analysis will have to be made for each of the designs considered, because of variation in the way the power system comes apart during an abort or reentry.

The power conditioning equipment will occupy a volume of about 27.8 M^3. This is a cylinder 3 m in diameter and 4 m long; its mass is of the order of 25,300 kg. Cables/bus bars to carry the load current will be sized for about 10,000 amperes exiting the MHD converter and for about 1000 amperes exiting the power conditioning equipment. Positioning and mounting of the cables/bus bars will have to be designed to sustain the forces between the lines during transients in the operating cycle. In addition, the power lines within the power conditioning equipment container will have to be positioned and mounted to sustain large forces during cycle operation.

MAINTENANCE

During the life of the power system, it is assumed that maintenance will be required for routine replacement or upgrading of parts, or to change or repair equipment. It is not defined whether the maintenance will be performed by man or by man-controlled robots. The onboard Instrumentation/Control subsystem and the Command and Control subsystem that monitor the status of many of the power system parameters will provide a continuous status of the power system. Conceptual designs of the power system assembly and installation shall include a definition of the parameters to be monitored and the maintenance required. The design shall be such that the power system can be disassembled to perform maintenance. The type and amount of radiation present from the reactor when maintenance is performed shall be specified. This will, in turn, define the amount of shielding required to protect the person or robot that does the maintenance.

Maintenance of the Instrumentation/Control subsystem and the Command and Control subsystem is to be a primary consideration. The amount and frequency of maintenance shall be dependent upon the redundancy provided in these two systems because they are monitoring the safety of the power system at all times.

RESUPPLY

Selection of the method of supplying hydrogen and cesium to the MMW/MHD power system will determine the need for resupply and the design of the tanks and tubing installation. If the tanks for the hydrogen and cesium are installed and filled before launch, and it is assumed that no leakage or excessive boiloff will occur during the 10 year life of the system, then the need for resupply for these two will not be required. The installation tubing can then be considered totally sealed and heat and leak proof.

However, if the tanks are to be launched empty, provision must be made in the design for filling the tanks in orbit. This filling function is tantamount to a resupply. The process of filling tanks in orbit presently is the subject of R&D technology contracts, but is not yet state-of-the-art. For this program, it will be assumed that the technology for filling the tanks will be developed when it is needed for this application. Filling of tanks in space involves connection, valving, control of the flows by pumping or static pressure, and the separation of liquids, vapors and gases. Of course, all of the functions must operate without leaks in the presence of zero gravity. Whether the filling functions and any resupply function can be accomplished without the intervention of humans is not yet determined. The technology of robotics is also in development at this time. Extra vehicular activity (EVA) required to assemble the large spacecraft in orbit has been done in space for simple tasks. Improvements in EVA capability are anticipated be made in the next few years.

To design the MMW/MHD power system structure and plumbing for the resupply function, consideration must be given to access for the operator or the robot to reach and manipulate valves, fittings and controls. If tools are required, there must be sufficient space for the tools to operate. The design must consider these factors.

If the MMW/MHD power system is designed without its own tankage so that the spacecraft can supply the hydrogen to the power system, the design of the plumbing and valving must be such that the plumbing connections can be made in orbit.

Resupply includes replacement of expendables and of depleted or deteriorated components. The technology for these functions will be developed for the space station and other large spacecraft to become operational within the next 5 to 10 years. Thus, it should be available for the period of this application.

Although dynamic analysis of the system is a Task 2 effort requiring more detailed component design information, some estimates of the reference system and component mass and inertial characteristics have been calculated to provide an indication of the system dynamic response for space manuevering and interfacing assessments. The calculations have been based on the system elements and arrangement shown in Figure 3-41. System geometry, mass, center of gravity location distribution and inertial information are presented for representative conditions for the space system and power system as noted in Figure 3-49 through 3-52. Element location, C.G. and inertial moments have been calculated relative to the interfacing plane between the power conditioning and neutral particle beam elements of the space system. For purposes of indicating the C.G. and inertial coupling with the neutral particle beam system, an assumption of NPB mass and geometry has been made.

ITEM	MASS KG	GEOMETRY	LENGTH METERS	RADIUS METERS	ROLL INERTIA C/G KGM-M-M	PITCH INERTIA C/G KGM-M-M	DISTANCE FROM NPB METERS	FIRST MOMENT KGM-M	MASS TIMES L*L
POWER CONDITIONER	25,300	SOLID CYLINDER	5.50	2.50	79,063	103,308	2.75	69,575	801,914
SHIELD	900	DISK	0.00	2.50	2,813	1,406	5.50	4,950	63,201
HYD. TANK (FULL)	5,300	SOLID SPHERE	2.50	2.50	13,250	13,250	6.75	35,775	491,499
REACTOR	2,200	SOLID CYLINDER	2.00	0.45	223	845	9.00	19,800	310,492
GENERATOR DISK	2,180	SOLID CYLINDER	1.00	1.00	1,090	727	10.50	22,890	390,270
NPB	36,000	SOLID CYLINDER	20.00	4.00	288,000	1,344,000	-10.00	(360,000)	1,825,030
TOTAL ASSEMBLY	71,880	KGM			384,438	1,463,536		(207,010)	3,882,406
ROLL INERTIA	384,438	KGM-M-M					CG =	-2.87993	
PITCH INERTIA	5,345,942	KGM-M-M							

CENTER OF GRAVITY -2.879938 METERS (FROM PC/NPB INTERFACE TOWARDS GENERATOR DISK)

Figure 3-49. Inertia and C.G. of Assembly with Full Hydrogen Tank - NPB Modelled as Solid Cylinders

ITEM	MASS KG	GEOMETRY	LENGTH METERS	RADIUS METERS	ROLL INERTIA C/G KGM-M-M	PITCH INERTIA C/G KGM-M-M	DISTANCE FROM NPB METERS	FIRST MOMENT KGM-M	MASS TIMES L*L
POWER CONDITIONER	25,300	SOLID CYLINDER	5.50	2.50	79,063	103,308	2.75	69,575	57,988
SHIELD	900	DISK	0.00	2.50	2,813	1,406	5.50	4,950	1,375
HYD. TANK (FULL)	5,300	SOLID SPHERE	2.50	2.50	13,250	13,250	6.75	35,775	32,757
REACTOR	2,200	SOLID CYLINDER	2.00	0.45	223	845	9.00	19,800	49,347
GENERATOR DISK	2,180	SOLID CYLINDER	1.00	1.00	1,090	727	10.50	22,890	84,777
NPB	0	SOLID CYLINDER	20.00	4.00	0	0	-10.00	0	0
TOTAL ASSEMBLY	35,880	KGM			96,438	119,536		152,990	226,243
ROLL INERTIA	96,438	KGM-M-M					CG =	4.263935	
PITCH INERTIA	345,779	KGM-M-M							

CENTER OF GRAVITY 4.2639353 METERS (FROM PC/NPB INTERFACE TOWARDS GENERATOR DISK)

Figure 3-50. Inertia and C.G. of Assembly without NPB with Full Hydrognen Tank

ITEM	MASS KG	GEOMETRY	LENGTH METERS	RADIUS METERS	ROLL INERTIA C/G KGM-M-M	PITCH INERTIA C/G KGM-M-M	DISTANCE FROM NPB METERS	FIRST MOMENT KGM-M	MASS TIMES L*L
POWER CONDITIONER	0	SOLID CYLINDER	5.50	2.50	0	0	2.75	0	0
SHIELD	900	DISK	0.00	2.50	2,813	1,406	5.50	4,950	5,116
HYD. TANK (FULL)	5,300	SOLID SPHERE	2.50	2.50	13,250	13,250	6.75	35,775	6,818
REACTOR	2,200	SOLID CYLINDER	2.00	0.45	223	845	9.00	19,800	2,739
GENERATOR DISK	2,180	SOLID CYLINDER	1.00	1.00	1,090	727	10.50	22,890	14,916
NPB	0	SOLID CYLINDER	20.00	4.00	0	0	-10.00	0	0
TOTAL ASSEMBLY	10,580	KGM			17,375	16,228		83,415	29,589
ROLL INERTIA	17,375	KGM-M-M					CG =	7.884215	
PITCH INERTIA	45,817	KGM-M-M							

CENTER OF GRAVITY 7.8842155 METERS (FROM PC/NPB INTERFACE TOWARDS GENERATOR DISK)

Figure 3-51. Inertia and C.G. fo Assembly without NPB, without Power Conditioner, with Full Hydrogen Tank

ITEM	MASS KG	GEOMETRY	LENGTH METERS	RADIUS METERS	ROLL INERTIA C/G KGM-M-M	PITCH INERTIA C/G KGM-M-M	DISTANCE FROM NFB METERS	FIRST MOMENT KGM-M	MASS TIMES L*L
POWER CONDITIONER	0	SOLID CYLINDER	5.50	2.50	0	0	2.75	0	0
SHIELD	0	DISK	0.00	2.50	0	0	5.50	0	0
HYD. TANK (FULL)	0	SOLID SPHERE	2.50	2.50	0	0	6.75	0	0
REACTOR	2,200	SOLID CYLINDER	2.00	0.45	223	845	9.00	19,800	1,226
GENERATOR DISK	2,180	SOLID CYLINDER	1.00	1.00	1,090	727	10.50	22,890	1,237
NFB	0	SOLID CYLINDER	20.00	4.00	0	0	-10.00	0	0
TOTAL ASSEMBLY	4,380	KGM			1,313	1,571		42,690	2,464
ROLL INERTIA	1,313	KGM-M-M					CG =	9.746575	
PITCH INERTIA	4,035	KGM-M-M							

CENTER OF GRAVITY 9.7465753 METERS (FROM PC/NFB INTERFACE TOWARDS GENERATOR DISK)

Figure 3-52. Inertia and C.G. of Reactor and Generator Disk

4.0 KEY TECHNICAL ISSUES

The key technical issues identified in Task 1 that pose questions of feasibility concern are discussed in this section. Only four of the issues identified are considered key issues for resolution in Task 2 in order to demonstrate the concept feasibility and justify continued development in Phase II. These are all related to a lack of directly demonstrated hydrogen plasma performance. The four feasibility concerns are, in order of priority: 1) plasma properties of hydrogen with cesium seed, 2) stable, full nonequilibrium ionization at low temperature (< 1800 K) and high Hall parameter design conditions, 3) endurance of disk generator performance for hundreds of seconds, and 4) energy extraction above 20 to 30%.

Justification for optimism in the affirmative resolution of these concerns of feasibility lies in the existing experimental demonstration of stable nonequilibrium plasma operation in Helium and Argon seeded with Cesium from the Tokyo Institute of Technology (TIT), Massachusetts Institute of Technology (MIT) and Eindhoven University of Technology (EUT) disk experiments.[(4-1)(4-2)(4-3)] First principle relationships give assurance that the hydrogen molecular characteristics should provide equivalent performance.[(4-4)(4-5)] Three reasons for this optimism are noted below:

- Stable nonequilibrium ionization has been demonstrated at MIT, TIT and Eindhoven with Helium and Cesium and Argon and Cesium in shock tunnel tests.

- Recent TIT experiments with He and Cesium at very low temperatures (< 2000 K) and seed fractions (~ 10^{-5}) have provided over 20% energy extraction with effective Hall parameters similar to that anticipated for this concept.[(4-6)]

- Both the velocity and molecular weight of hydrogen favor equivalent to better performance with the temperature and pressure ratios available for this concept.

4.1 Technical Issues Identified

Key outstanding technical issues were identified in Task 1120 at the system and subsystem levels, formed into an evaluation matrix and critiqued by a group of experts. Those that were considered to constitute a feasibility concern form the basis for the proposed research and development program to be accomplished during Task 2.

The issues identified at the overall power system level are:

- Operational dynamics of the total system-steady state and transient; these are subject to analysis by hybrid computer simulation.

- Dynamic response of components and working fluid to rapid changes in pressure, temperature and magnetic field; analysis predictions with experimental verification will be essential.

- Control system design and philosophy; control system design will be developed by control studies and analytical experiments with a hybrid thermohydraulic/controls simulation model.

The issues for the disk MHD generator and the selected working fluid are listed below. All except the effluent question will require experimental verification, although test articles of subscale geometry and power levels will adequately resolve the issues for this feasibility assessment.

- Hydrogen plasma properties.

- Behavior of the cesium seeded hydrogen working fluid in the disk generator as designed.

- Capability of the disk generator to achieve nonequilibrium ionization and the associated high expected power density/enthalpy extraction.

- Endurance capability of the disk generator, since testing to date has been for milliseconds; testing for tens of seconds will be required.

- Performance of the innovative use of return field of the conceptual disk configuration.

- Acceptability of the very lightly seeded hydrogen as an effluent; analyses and a study of research performed to date are expected to provide adequate resolution.

- Materials and fabrication of disk to assure integrity and reliability over long periods in space with periodic cyclic operation.

Issues related to the nuclear reactor heat source are tabulated below. It is important to note that all of these issues are addressed in other programs related to use of the NERVA derivative reactor in other types of SDI power systems or in space propulsion applications. These issues are:

- Capability to operate at 3000 K with the low required power density; this is primarily a fuel element hot end configuration issue.

- Nuclear and magnetic radiation impacts on sensors, instrumentation and controls for extended periods of time, potentially aggravated by space vacuum; this issue is also listed for the overall control components.

- Cesium seed impact on reactor fuel and materials over extended space environment.

- Disposition/containment of reactor core in event of reentry (not a radiation hazard unless operated at power).

- Permanent shutdown and disposal of reactor.

Issues related to the power conditioning system are:

- Need for current and voltage controls for the power fed back to the disk generator magnet.

- Development of specific power conditioning circuits and packaging concepts based on extrapolation of 1990s component capabilities and identification of needed development efforts.

- Evaluation of methods of transmitting electrical power at high voltages and currents in space.

- Characterization of the "noise" at the generator output terminals which will be superimposed on the DC component; a special measurement package added to a subscale disk generator test can provide the necessary information.

- Knowledge update of environmental effects on electrical and power conditioning components, an issue shared with the control system.

Issues related to the control system are:

- Response time, characteristics, and accuracy requirements of control loops, subject to analytic studies supported by the system simulation model.

- Control circuit reliability over a long term in a space, magnetic, and nuclear radiation environment without opportunities for inspection or maintenance.

Figure 4-1 lists the key technical issues, and Figure 4-2 presents the development efforts and tests defined for resolving these issues with priorities noted. The logic has been defined to provide the decision basis needed for confident continued effort. Some schedular impacts could be

Key Issue	Priority	Method of Resolution	Comments Tests & Facility Requirements
Hydrogen Plasma Properties	1	Plasma Experiments	MIT Shock Tunnel Tests
Disk Generator Nonequilibrium Performance	1	Disk Generator Experiments	MIT Shock Tunnel Tests
Endurance of Nonequilibrium Performance	1	Disk Generator Experiments	Steady State Experiment (TBD Facility) Testing - Up to 100 S
High Energy Extraction-Low Plasma Temp., Low Seed Concentration	1	Disk Generator Experiments	MIT Shock Tunnel and Steady State Experiment Tests. Also, Empirical Verification from TIT & Eindhoven Disk Generator Experiments

Figure 4-1. Key Technical Issue and Resolutions

Experiment	Data Needed	Priority	Issues Addressed	Critical Schedule	Impacts	Task Definition
Plasma tests with existing MIT shock tunnel and disk	• Conductivity data • Electron energy loss factor • Hall parameter (effective)	1	• Plasma properties of hydrogen with cesium conductivity performance • Nonequilibrium ionization	• Initial conductivity demonstration by Month 3 to initiate design effort • Plasma properties confirmed by Month 9 for analytical model	• Hydrogen carrier plasma model development • Analytical task effort initiation • Requirements for generator test • Disk design effort initiation	WBS 1220, 1230
Disk generator tests with modified MIT disk and magnet	• Stable region for full nonequilibrium ionization	3	• Energy extraction constraints	• Confirmation by Month 14 of energy extraction	• Definition of disk design parameters for analytical model needed to assess disk design	
Endurance experiment with hydrogen-driven disk generator	• Energy extraction, performance/endurance trends, and design data	2	• Effects of duration and level of nonequilibrium ionization on MHD disk performance	• Confirmation by Month 22 of design feasibility	• Phase II Development Program Plan and initiation	WBS 1250, 1260

Figure 4-2. Feasibility Issue Resolution Schedule

averted with somewhat higher risk by running parallel efforts. Also, a few significant development areas are noted where extension to provide additional confidence is not demanded. Although some of these early physics-type experiments could be carried out in facilities other than those identified, the impact upon continued efforts of alternative facilities would suggest these to be less desirable.

An outline of the preliminary R&D Plan was prepared to describe the framework of a program which addresses the highest priority issues. The objective is the resolution of technical uncertainties to the extent necessary to complete the Phase I goals of this feasibility assessment.

4.2 Key Feasibility Issue Priorities

The technical issues identified as needing resolution to proceed confidently into the Concept Development program are prioritized in the following section with comments relative to the impact they have on the program. The priorities are defined relative to both effort and cost as well as technical risk. No feasibility issues were identified for areas where design and experimental precedence existed, and the space power concept could be developed but possibly would be penalized by uncertainties.

4.3 Disk MHD Generator Engineering Issues

Only two areas appear to present engineering or material questions that have not be an adequately resolved with feasibility demonstrated. Those requiring further consideration in Task 2 to assure meeting performance, cost and schedular goals are principally related to electrical insulation: 1) the disk and nozzle isolation and reactor core isolation, and 2) coated composite and titantium materials selection with the space environment impact. The variance from state-of-art materials, engineering and fabrication identified in Task 1 are listed in Figure 4-3. Comments on the problems and methods of solution including effort, cost and schedule estimates have been developed to assist in determining the scope of the disk development program.

Problems	State-of-the-Art Available	Being Developed	Not Available	Development Required
• Attachment Method of Ceramic Liner to Structural Material	X			Standard methods require refinement and testing.
• Thermal and Electrically Isolating Disk Walls-Ceramic Between BN & Structure	X			
• Electrical Insulating Coating on Structural Metal	X			Temperature cycling tests.
• Select Composite Materials for Cooler Areas	X	X		
• Cooled Electrode Fabrication	X			Requires refinement.
• Constant Inlet Nozzle Gap	X			Test in WBS-1250.
• Generator Cooling Capability	X			Verify in WBS-1250.
• Cesium Distribution System	X			Requires performance tests.
• Electrically Insulating Coolant Conductor	X			Fabricate and proof test.
• Fluidic Thrust and Vector Control	X			Fabricate and demonstrate.
• Electrode Material to Conductor Material Joint	X			Fabricate and demonstrate.
• Titanium Coating to Assure Compatibility With H_2		X		Fabricate and demonstrate, or use alternative material.

Figure 4-3. Status of Design or Fabrication Issues for Disk Generator

5.0 RESEARCH AND DEVELOPMENT PLAN

The Research and Development (R&D) Plan for Task 2 consists of the analytical and experimental investigations necessary to: (1) validate high interaction MHD disk performance, and (2) confirm the viability of the MHD disk power system concept. The purpose of the plan is to define the program and effort necessary to provide all information and demonstration required for completion of the space system specification. The R&D Plan outline initially proposed has been reviewed and revised in accordance with the contract Statement of Work and the Task 1 conceptual design and key technical issue results.

The R&D Plan addresses the technical, management and cost aspects of the Task 2 analytical and experimental investigations. The content is summarized in the following paragraphs.

Section 5.1, Technical Work Plan, presents the technical approach and work statements required to address the key technical issues described in Section 4.0 and to achieve the Task 2 objectives. The schedule and key milestones are presented.

Section 5.2, Management and Personnel, describes the project management and organization. The responsibilities of the key personnel are defined along with their qualifications and the qualifications of supporting personnel.

Section 5.3, Research and Development Plan Costs, provides budgetary cost estimates for the analytical and experimental work during Task 2.

The R&D Plan is consistent with the Task 2 Statement of Work and is designed to address and resolve the highest priority technical issues to the extent necessary to achieve the Phase I feasibility assessment objectives.

5.1 Technical Work Plan

The content of the Task 2 R&D Plan consists of shock tunnel and disk generator experiments supplemented by additional analysis and component development. These activities, their relationship to the key technical issues identified in Task 1, the technical approaches to be used, and the WBS subtasks and schedule are defined in this report section.

Task 1 results from the system conceptual design and key technical issues evaluations have been used to refine the originally proposed R&D plan. Two major experimental efforts are identified that are necessary to verify the hydrogen plasma properties and demonstrate the high performance potential of the MHD disk generator. These two experimental efforts are interrelated and synthesized by a system analysis subtask that focuses on the steady state and dynamic performance modeling of the complete MHD power system. This system analysis subtask also serves as an integrating factor for the experimental efforts.

The two major experimental efforts are supplemented by additional analytical and component development subtasks which focus on materials, structural, electrode, seed, power conditioning, and system interaction issues. All of the proposed experimental and developmental results will culminate in the refinement of the 100 MW_e space power system conceptual design and the resolution of the key technical issues.

5.1.1 Major Experiments

The two major experimental efforts are the interrelated shock tunnel experiments and the disk MHD generator energy extraction experiment. The feasibility issues these experiments are designed to address and the analytical/experimental logic for the testing is summarized in Figure 5-1. Assessments have been made of the experimental efforts and the hardware and facilities needed for the testing. The shock tunnel experiments will be accomplished at MIT with only minor facility modifications. The cost and schedule implications for the high energy extraction disk MHD generator experiment are more significant. Electrical arc heating equipment, consisting of a plasma torch and matched power supplies, is needed to heat the hydrogen for the disk energy extraction equipment. The electrical power input required from matched power supplies to create the plasma conditions

Feasibility Issues

1. H_2 with Cs plasma performance: Issue is nonequilibrium ionization

   - Plasma H_2 + Cs + Ar Property Determination - (Verification of 100% nonequilibrium ionization with operating conditions)

   - Analytical Model Verification - (H_2 + Cs electron temperature, energy loss factor - δ', conductivity, etc.)

2. Disk generator performance demonstration:

   - Demonstrate energy extraction at desired disk operating conditions

   - Demonstrate adequacy of disk generator analytical model

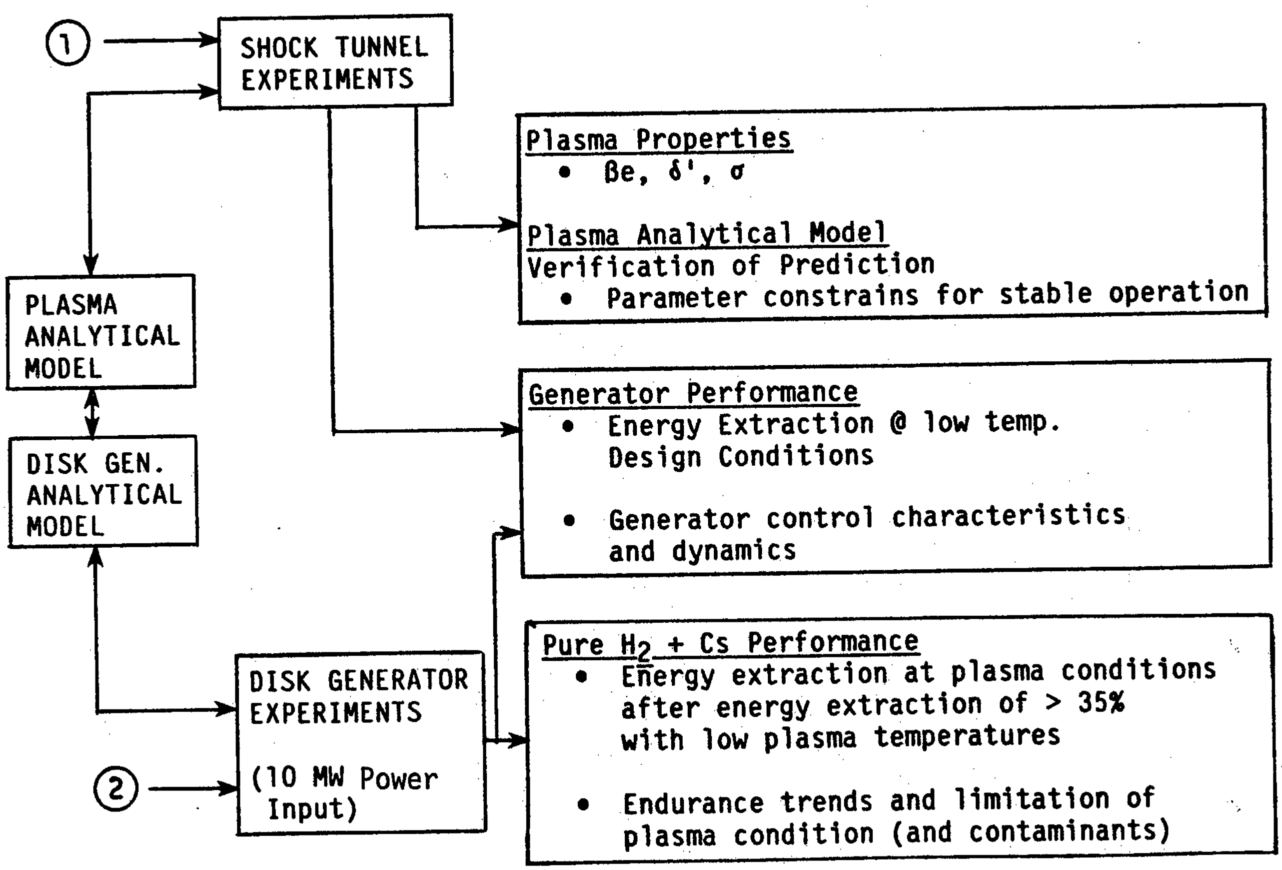


Figure 5-1. Task 2 Experiment and Analysis Logic

necessary for the experiment is in the 10 MW_e range. Available options with regard to the electrical arc heating equipment are:

1) purchase and install new equipment

2) move existing equipment and install at the test site

3) use existing equipment presently installed at a test site.

Alternate test sites for the energy extraction experiment where the above three options are applicable are listed in the facility evaluation matrix of Figure 5-2. The use of the lowest cost (option 3) electrical arc heating equipment option will reduce the Task 2 facility cost by $700,000 to $1,900,000 compared to options 1) or 2). The schedule impact for option 1), the purchase of new equipment, has not been specifically determined but is expected to be severe in view of the overall Task 2 schedule of 24 months. Facility modifications will also impact the schedule but will only require straightforward engineering without technical breakthroughs.

The Task 2 schedular and budgetary goals are ambitious, and careful and prudent evaluation of the facility alternatives is required early in Task 2 to finalize the facility selection.

5.1.1.1 Shock Tunnel Experiments

Two types of experiments will be conducted in the MIT shock tunnel facility illustrated in Figure 5-3:

- plasma property experiments

- generator performance experiments

Facility	Facility Availability	Site Accessibility	Hydrogen Operation	Electric Arc Heater Option(s)	Extent of Required Modifications	Cost Impact	Potential for Schedule Impact
CDIF	Yes	Fair	Yes	1, 2	Major	Nominal	Nominal
(W) Plasma Center	Yes	Good	Yes	3	Minor	Low	Low
MIT	Yes	Good	Yes	1, 2	Major	Nominal	High
Eindhoven	Yes	Poor	Yes	1, 2	Major	High	High
Tokyo Inst. of Tech.	Yes	Poor	Yes	1, 2	Major	High	High

Electrical Arc Heater Equipment Options (Plasma Torch/Matched Power Supplies)

1) Purchase/Install New Equipment

2) Move Existing Equipment from Another Site/Install/Remove

3) Use Existing Equipment at Present Site

Figure 5-2. Facility Site Assessment for High Energy Extraction Disk MHD Generator Experiment

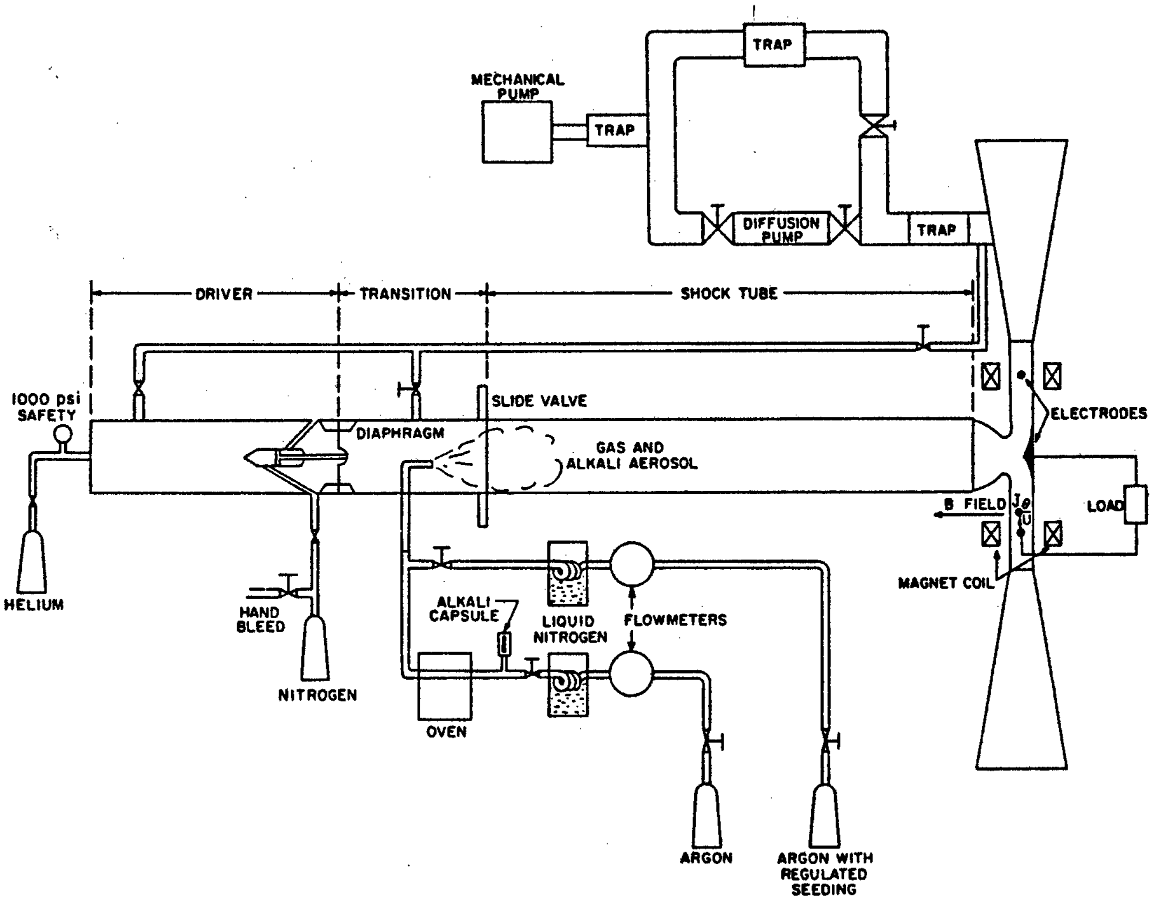


Figure 5-3. Diagram of the MIT Alkali Shock Tunnel and MHD Generator

The MIT shock tunnel facility[5-1][5-2] is designed such that:

- the test sections of the disk generator are driven in a shock tunnel under tailored conditions

- the experiment flow time is more than an order of magnitude shorter than the total test time; i.e., steady flow conditions are fully developed prior to the experiment.

- the seed is uniformly vaporized and ionized at the entrance of the test section or disk.

- the wall temperature rise during the start of test operation is negligible when compared to the large temperature difference between the wall and the gas recovery temperature.

The shock tunnel experiment is of particular value for needed parametric studies because of the ease with which each key parameter can be changed (e.g., pressure, temperature, gas composition, seeding rate and the Hall coefficient).

The steady flow characteristics in the test section disk generator have been verified by pressure, voltage and electron density measurements not only in the MIT facility but also in other similar facilities, e.g., Eindhoven Technical University[5-3] and Tokyo Institute of Technology.[5-4] Disk generator tests have proven not only repeatable at one facility but the MIT tests on the argon driven disk generator with swirl were replicated at Eindhoven University.[5-4] A comparison of these test results is shown in Figure 5-4. Continuing experiments at TIT with helium and cesium at very low loadings have corroborated the plasma physics and disk design understanding, is discussed in Section 4.0.

Because of the short exposure time to corrosive conditions (< 1 min.) and the low energy deposition at the walls, no material problems exist in the

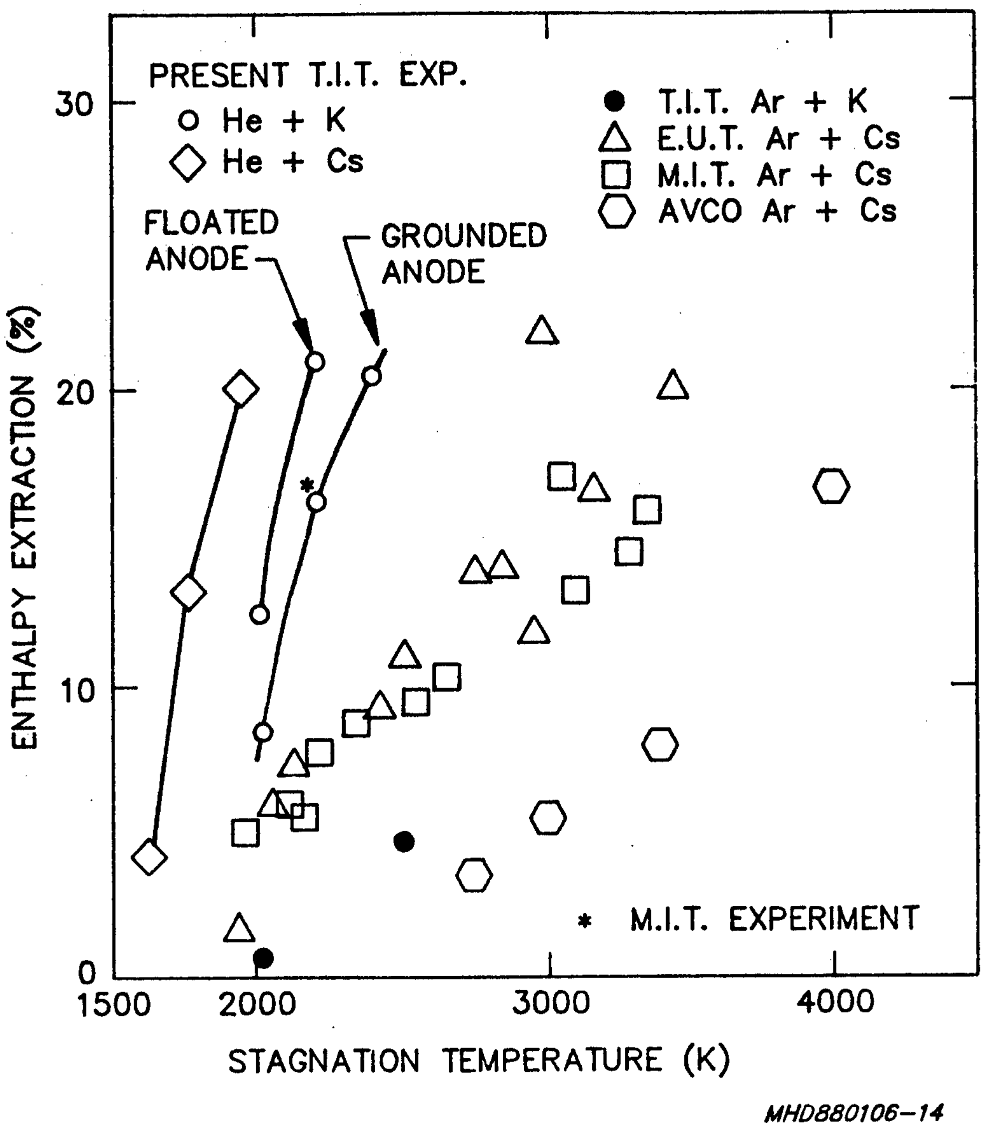


Figure 5-4. Enthalpy Extraction vs. Stagnation Temperature. (The enthalpy extraction marked with * from Ref. 5-2 is added to the original figure (from Ref. 5-4).)

shock tunnel experimental tests, and excellent electrical insulation is maintained.

Since the characteristic experimental ionization times in the bulk of the plasma (τ <10μs) and near the wall (τ <1ms, interelectrode breakdown), are less than the total test operating time, the shock tunnel experimental results are representative of plasma phenomena in longer duration test facilities with ideal walls. With the "ideal" wall provided in shock tunnel disk generator experiments, electrical fields up to 38 kV/m have been developed in the plasma.[5-2]

Tests in the shock tunnel experimental hydrogen driven disk generator will enable determination of wall phenomena which can lead to limitations of the Hall field caused by a coupling between the plasma and the wall materials. Therefore, the shock tunnel experiments will permit the determination of both the plasma physical and fluid mechanical characteristics of the flow. However, surface phenomena with a time scale larger than a few milliseconds are not duplicated in the shock tunnel.

The specific experiments to be conducted in the MIT shock tunnel facility are described below.

PLASMA PROPERTY EXPERIMENTS

Objectives

The overall objective of the plasma property experiments is to develop a sound understanding of the plasma properties expected in the nuclear driven MMW disk generator. The specific objectives are:

1) to demonstrate: a) nonequilibrium ionization
   b) full-seed ionization
   c) level of plasma uniformity

2) to determine: a) inelastic energy loss factor

b) effective Hall coefficient versus microscopic Hall coefficient.

Discussion

The key property in these experiments is the conductivity of the plasma. Since the electron hydrogen momentum exchange is well known,[5-7] the uncertainty with regard to conductivity involves the determination of the electron density and temperature.

Correct evaluation of these parameters depends on the determination of the inelastic loss factor for plasma conditions represenative of the MMW disk generator (hydrogen gas temperature ~ 1600 K and electron temperature in the range of 1600 to 5000 K). The inelastic energy parameter is an overall parameter which gives the total energy loss by the electrons incurred in the kinetic processes indicated in Figure 5-5. As indicated in this figure, the electronic or excitation temperature of the cesium atom can be expected to be very close to the electron temperature and the translational and vibrational temperatures to be nearly identical. Therefore, the vibrational temperature is the critical element which influences the energy loss factor. The vibrational temperature will relax from its stagnation value in the reaction during the expansion through the nozzle and the generator. This temperature will be kinetically determined.

The test program will determine the electron temperature and density from the free-bound continuum[5-1] and the vibrational temperature from the band radiation of hydrogen. The static pressure distribution will also be determined using Kistler gauges as will the electrical field in the test section. The latter will be a disk configuration without electrodes.

The tests will be conducted for three cesium concentrations of 5×10^{-5}, 1.5×10^{-4} and 5×10^{-4}. The values of the Hall coefficient will be 0, 2, 4, 6 and 8. The static temperatures will be 1400, 1600 and 1800 K. The

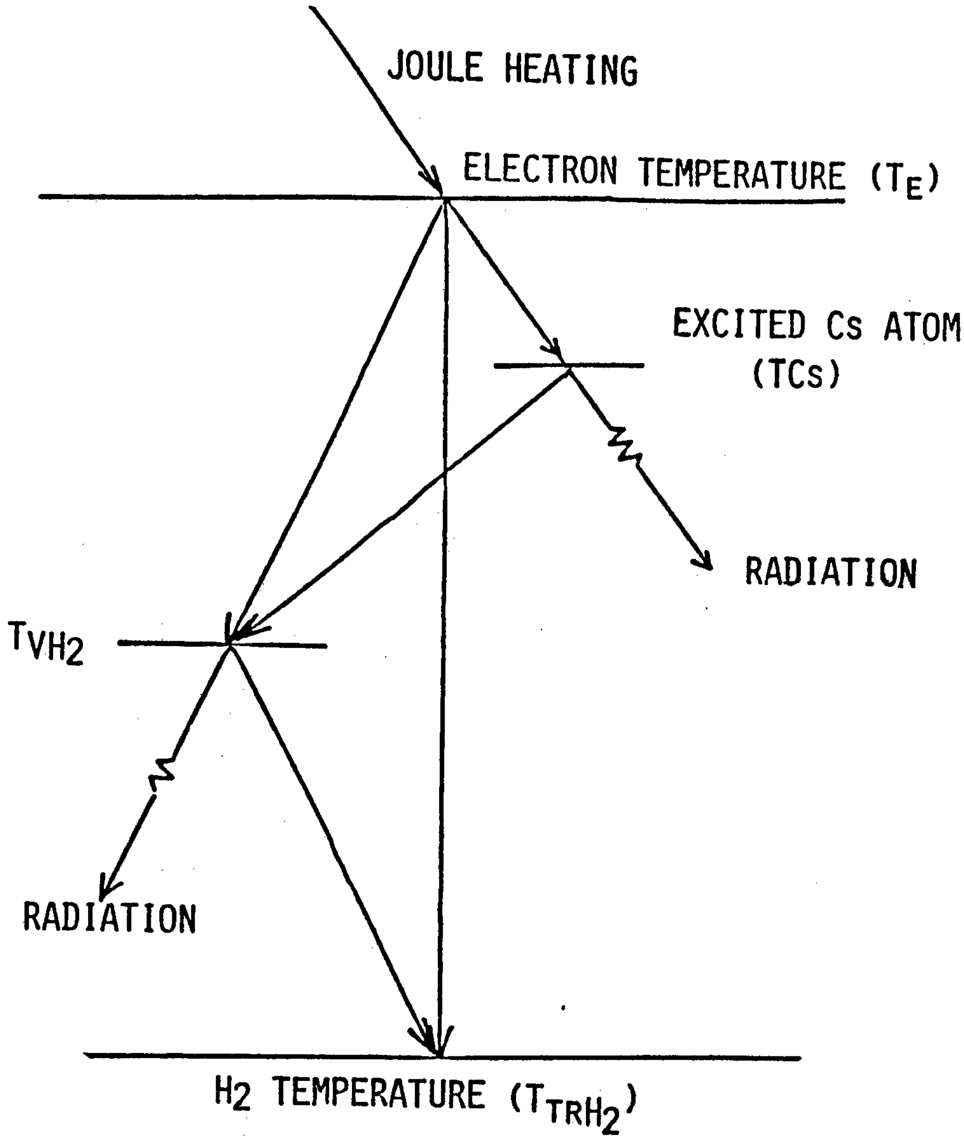


Figure 5-5. Kinetic Processes Between Electrons, Hydrogen and Cesium

data will first allow the determination of the loss factor, the verification of the kinetic model for the hydrogen, and the conductivity of the plasma. The level of non-uniformity of the plasma will also be measured from local fluctuations in electron density and electrical field.

The average radial electrical field will allow the determination of the effective Hall coefficient. The results of this investigation will be used to establish the kinetic model for the electron density and the vibrational relaxation of hydrogen. This kinetic model will be introduced in the advanced analytical model of the generator.[5-6] The inelastic loss factor will be introduced in the simplified analytical model (SPA) of the disk generator used in the systems analysis. This model assumes that Saha equilibrium for the electrons exists at the electron temperature.

The initial experiments will begin wtihin the first month as no hardware modifications are required. Data for assessing continued testing will be produced within the first two months which can be related to the analytical model and permit initiating test planning for the disk generator experiment.

Personnel/Schedule

The personnel for this task will be Professor Louis, a Westinghouse engineer dedicated to this effort, a technician, and a graduate student. Within three months the initial hydrogen plasma effects will be obtained. The task will take nine months to fully gather the data, with three months for analysis and development of the kinetic model.

GENERATOR PERFORMANCE EXPERIMENTS

Objectives

The main objectives of the shock tunnel generator performance experiments are to verify the analytical model used for the generator and to confirm operating configurations and conditions which are stable. Stability limits will be compared with the theoretical predictions based on the unsteady model of Lin and Louis[5-6] modified for hydrogen.

Discussion

The disk generator configuration to be tested will be a reduced size model of the 100 MW_e space power system configuration including the radial section within the magnet radius and the section beyond the outer magnet radius. The shock tunnel is a flexible facility so that the inlet thermal power carried by the gas can be as high as 7 MW_t. Hall coefficients up to 15 can be also attained with the proposed magnet. The tests will be run with conditions representative of the space power system, (e.g., static temperature of gas 1500 to 1600 K, electron temperatures in the range of 3500 to 5500 K, and Hall coefficients in the range of 4 to 13). Both the inner radial section and outer radial section of the disk (Figure 5-6) will have 3 electrodes with one electrode (electrode 3) common to both for a total of five electrodes.

The tests will be conducted to verify the advanced analytical model, including the electron and hydrogen kinetics, by focusing first on the performance and stability limits of the inner radial sections operating with a double load and later with a single load.

The focus will be on the outer section during these tests, a configuration which has never been studied thus far. In these tests, the inner radial section will be short circuited and the outer radial sections will be operated with a single load first and later with a double load. The performance of the disk generator will be assessed and compared to the advanced kinetic analytical model. Stability limits of the outer radial sections of the disk will be determined and compared with the results of the analytical model of Lin and Louis.[5-6]

Guided by the above results, the performance of the complete (inner and outer radial sections of the disk) generator will be determined for single and multiple loads and compared with the analytical model. The stability limits of the whole generator will be determined for the same loads and again compared with the analytical model of Lin and Louis[5-6] modified for hydrogen.

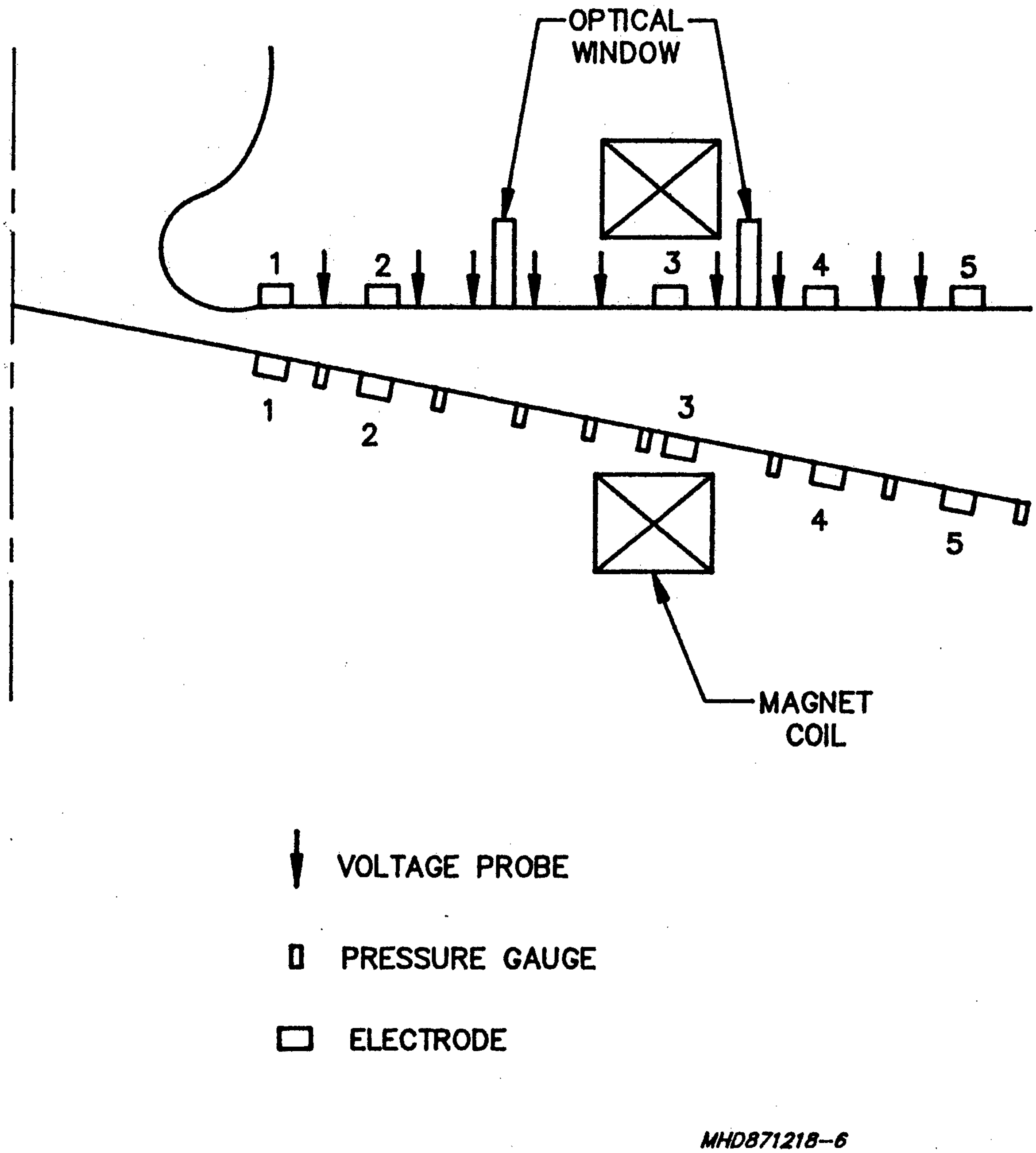


Figure 5-6. Instrumentation of the Disk Generator in the Shock Tunnel

Personnel/Schedule

The personnel involved will include Professor Louis, a Westinghouse test engineer, a technician and a graduate student. Initial energy extraction demonstrations will be conducted with the existing disk and magnet that will provide needed data for disk design within the period of developing plasma properties during the first nine months. The new disk and the 5 T magnet will be designed and built during the first year. The high energy extraction tests will be conducted during the first eight months of the second year, and analysis of the data and analytical model verification will be completed by the end of the eleventh month of the second year.

5.1.1.2 Disk MHD Generator Energy Extraction Experiment

Objective

The objective of this experiment is to demonstrate high interaction MHD disk performance and to verify that the 100 MW_e/500 s MHD power system will attain a high extraction.

Discussion

The feasibility issue addressed in this experiment is the ability to extract significant energy from the disk generator at low gas temperature and high pressure ratios not previously demonstrated with hydrogen gas. The specific concern is the generator's capability to maintain stable high power density and energy extraction performance when stagnation temperature and pressure ratios reach those predicted for the disk beyond the 20 to 35% extraction point, and for the outer radial section. Desired conditions for operating a stable plasma with higher energy extraction require maintaining 100% seed ionization with stagnation temperatures below 2000 K and stagnation pressures of the order of one atmosphere. This experiment is designed to provide similar plasma conditions (static temperature and Joule heating) and demonstrate the predicted performance and endurance capability. Design conditions and a test matrix to explore the disk generator characteristics for analytical model verification are illustrated in Figure 5-7.

Feasibility Issue: Energy Extraction

1. Demonstrate duration capability and power extraction at desired disk generator operating conditions. The important conditions to simulate are static gas temperature and Joule dissipation leading to expected electron density and temperature.

2. Establish stable operating limits:

   - Temperature, pressure, seed, B field and Mach No., control, and (single or multiple) loading

3. Verify disk generator analytical model (characterization comparisons)

Design Conditions Established for Disk MHD Generator Experiment:

B Field	4.0 T
Inlet Pressure	1.25 Atm
Flow Rate	0.18 kg/s
Mach No.	1.3
Plasma Temperature	1800 K (2000 K Tot.)

<u>Test Matrix</u>

Mass Flow (kg/s)	Total Temp. (K)	Static Temp. (K)	Mach No.	B Field (T)	Time (s)	K Loading
0.21	1700	1308	1.4	3.5	1-5	*
0.2	1800	1384	1.3	2.5, 3.5, 4.0	1-5	*
0.18	2000	1538	1.3	3.5	1, 100 1-5	0.45 *
0.17	2200	1692	1.3	3.5	1-5	0.45
0.15	2500	1923	1.3	3.5	1-5	0.45
0.12	3000	2308	1.3	2.5, 3.5, 4.0	1-5	*

*0.55
0.50
0.45
0.40
0.0 (O.C.)

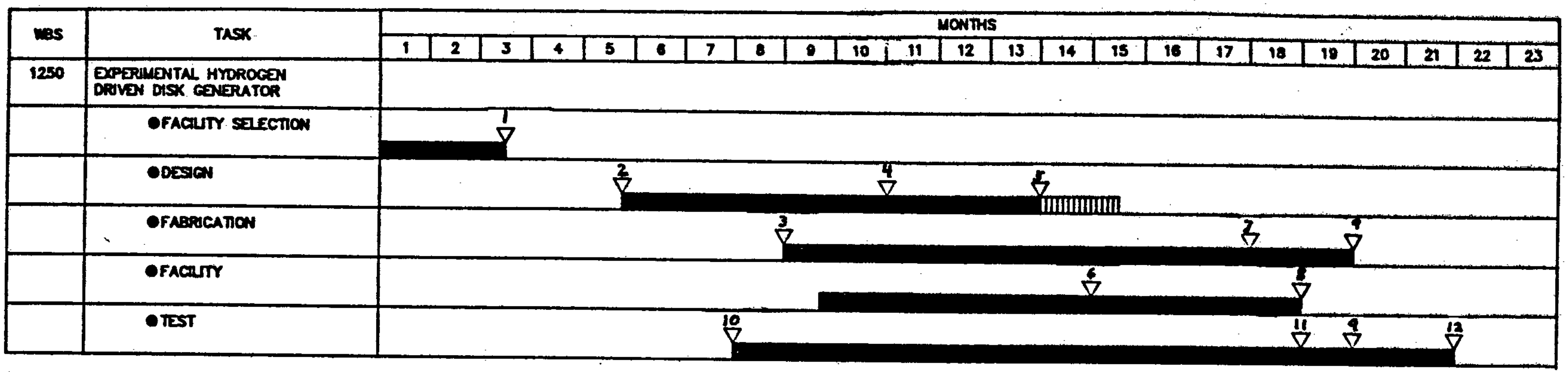
Figure 5-7. Disk MHD Generator Energy Extraction Experiment Summary

The 100 s testing of the disk MHD generator in the arc heated configuration involves completion of the following subtasks:

- Facility Selection
- Design and construction of a hydrogen heat source using electric arcs and mixing chamber
- Design and assembly of nozzle, disk generator and diffuser designed for subatmospheric test conditions
- Design and construction of a cryogenically cooled magnet
- Test of hydrogen arc heat source and measurements of the conductivity at the outlet of the mixing chamber.
- Test of electrode segments
- Tests of nozzle and diffuser
- Test of magnet
- Test of hydrogen arc heated disk generator at design conditions

The tentative schedule for accomplishing these activities and efforts as presented in the proposal has been reviewed and revised as shown in Figure 5-8.

Cost for conduct of these tasks will be highly contingent on the selection of the test facility site and on equipment availability. Three facility options (Figure 5-9), with regard to the disk generator energy extraction experiment, were preliminarily investigated: Option 1 would utilize the CDIF in Butte, Montana with power supplied to the arc heater power supplies at 4800 V (requires new equipment to transform voltage from 4160 to 4800 V);



1. Facility review and recommendation completed.
2. Initiate endurance experimental disk generator design.
3. Order long lead materials.
4. Preliminary design review.
5. Endurance generator design complete.
6. Plasma torch procurement complete.
7. Endurance generator fab/assembly complete.
8. Test facility modifications complete.
9. Test article installed and checked out.
10. Preliminary test plan issued.
11. Final test plan.
12. Endurance disk generator tests complete.

Figure 5-8. Milestone Schedule for Experimental Hydrogen Driven Disk Generator Test

Electric Arc Heater Option(s)	Facility	Site Accessibility	Extent of Required Modifications	Estimated Cost Savings ($)	Potential for Schedule Impact
1	CDIF	Fair	Major	0	Nominal
2	CDIF	Fair	Minor	700,000	Low
3	(W) Plasma Center	Good	Minor	1,900,000	Low

Electrical Arc Heater Equipment Options (Plasma Torch/Matched Power Supplies):

1) Purchase/Install New Equipment

2) Move Existing Equipment from Anther Site/Install/Remove

3) Use Existing Equipment at Present Site

Figure 5-9. Estimated Cost Impact Due to Facility Options for Experimental Hydrogen Disk Generator Testing

Option 2 would utilize the CDIF with power supplied to the arc heat power supplies at 4160 V which would require a reduction (~ 15%) of power input to the test article; Option 3 would utilize the Westinghouse Plasma Center. Both Options 1 and 2 require moving two 5 MW arc heater power supplies from the Plasma Center and returning the power supplies after the testing period. The estimating basis was developed from test article definition and operating data illustrated in Figures 5-10 through 5-12.

	Radius (m)	Height (m)	Static Pressure (Pa)	Static Temperature (K)	Velocity (m/s)	Mach Number (-)	Swirl (-)
1	0.80000E-01	0.12076E-01	44150.	1431.2	3938.9	1.4000	0.00000
2	0.90000E-01	0.12361E-01	39946.	1431.1	3780.7	1.3438	-0.89416E-02
3	0.10000	0.12925E-01	35991.	1431.1	3612.1	1.2839	-0.17779E-01
4	0.11000	0.13787E-01	32288.	1431.1	3432.1	1.2199	-0.26856E-01
5	0.12000	0.14995E-01	28838.	1431.1	3239.5	1.1514	-0.36482E-01
6	0.13000	0.16642E-01	25644.	1431.1	3031.6	1.0775	-0.47156E-01
7	0.13842	0.18468E-01	23153.	1431.1	2843.0	1.0105	-0.57336E-01

	Stagnation Pressure (Pa)	Stagnation Temperature (K)	Density (kg/m^3)	Electrical Conductivity (mho/m)	Electron Mobility (1/T)	Hall Parameter (-)	Reynolds Number (-)
1	0.13817E+06	1904.2	0.75284E-02	29.275	1.6454	5.7588	93212.
2	0.11553E+06	1868.4	0.68116E-02	28.852	1.7880	6.2581	91068.
3	95879.	1831.4	0.61371E-02	28.411	1.9516	6.8307	87103.
4	78972.	1793.2	0.55057E-02	27.970	2.1400	7.4901	81672.
5	64573.	1754.7	0.49175E-02	27.543	2.3584	8.2543	75112.
6	52388.	1715.4	0.43728E-02	27.148	2.6135	9.1471	67714.
7	43681.	1681.8	0.39482E-02	26.857	2.8631	10.021	61050.

	Electric Field (V/m)	J Radial (A/m^2)	J Tangential (A/m^2)	Power Density (W/m^3)	Integrated Power (W)	Loading Factor (-)	Electron Temperature (K)
1	-43850.	30437.	-0.22820E+06	-0.13347E+10	0.00000	0.44740	4318.5
2	-45884.	26432.	-0.21631E+06	-0.12128E+10	82887.	0.44499	4484.3
3	-47952.	22750.	-0.20371E+06	-0.10909E+10	0.16956E+06	0.44314	4653.7
4	-50035.	19388.	-0.19064E+06	-0.97009E+09	0.26008E+06	0.44167	4825.4
5	-52099.	16340.	-0.17720E+06	-0.85129E+09	0.35444E+06	0.44047	4996.0
6	-54058.	13591.	-0.16341E+06	-0.73473E+09	0.45253E+06	0.43950	5158.9
7	-55544.	11502.	-0.15154E+06	-0.63888E+09	0.53781E+06	0.43882	5282.6

Figure 5-10. 100 Second Disk Generator Experiment Internal Parameters

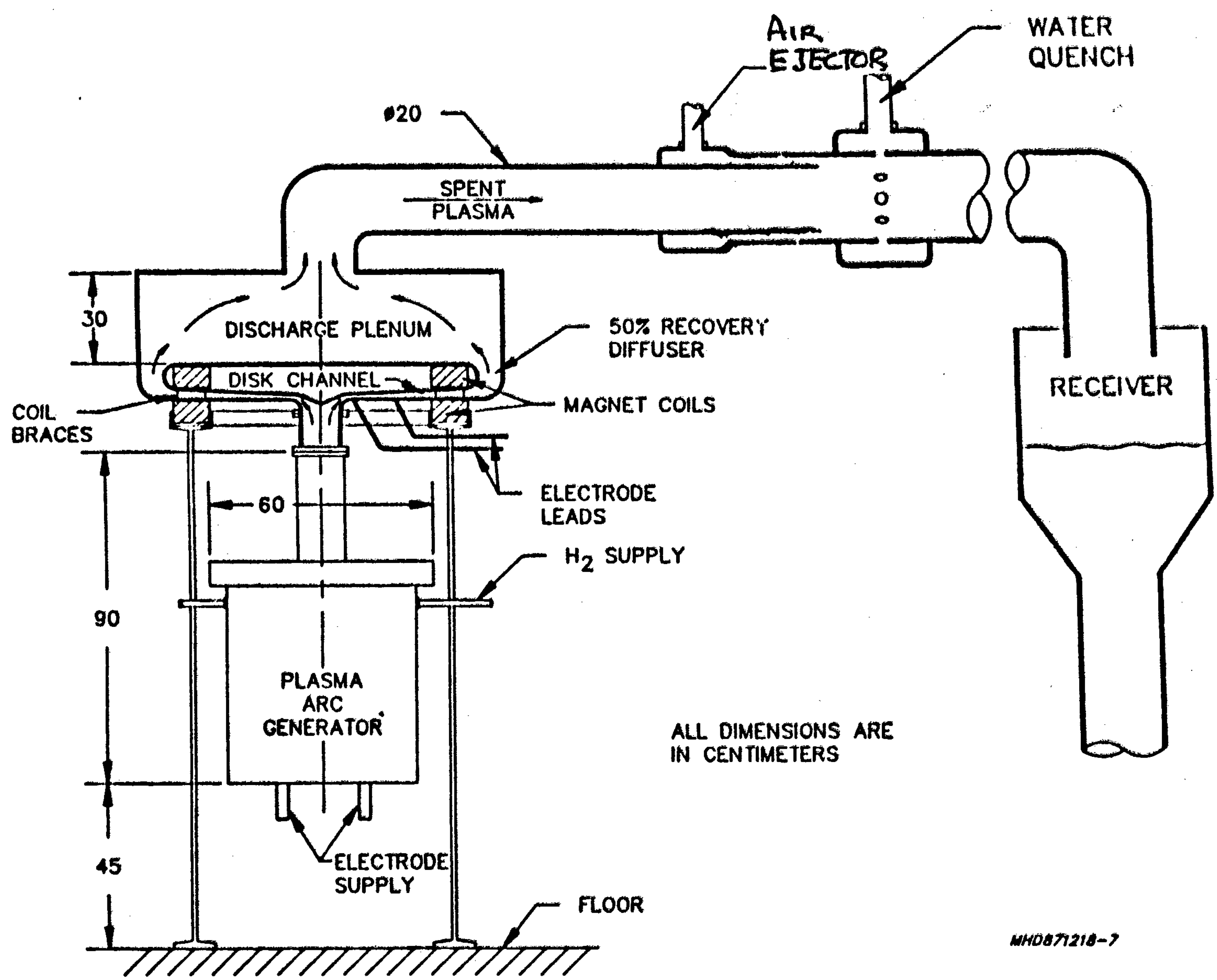


Figure 5-11. Experimental Hydrogen Disk Generator Test Configuration

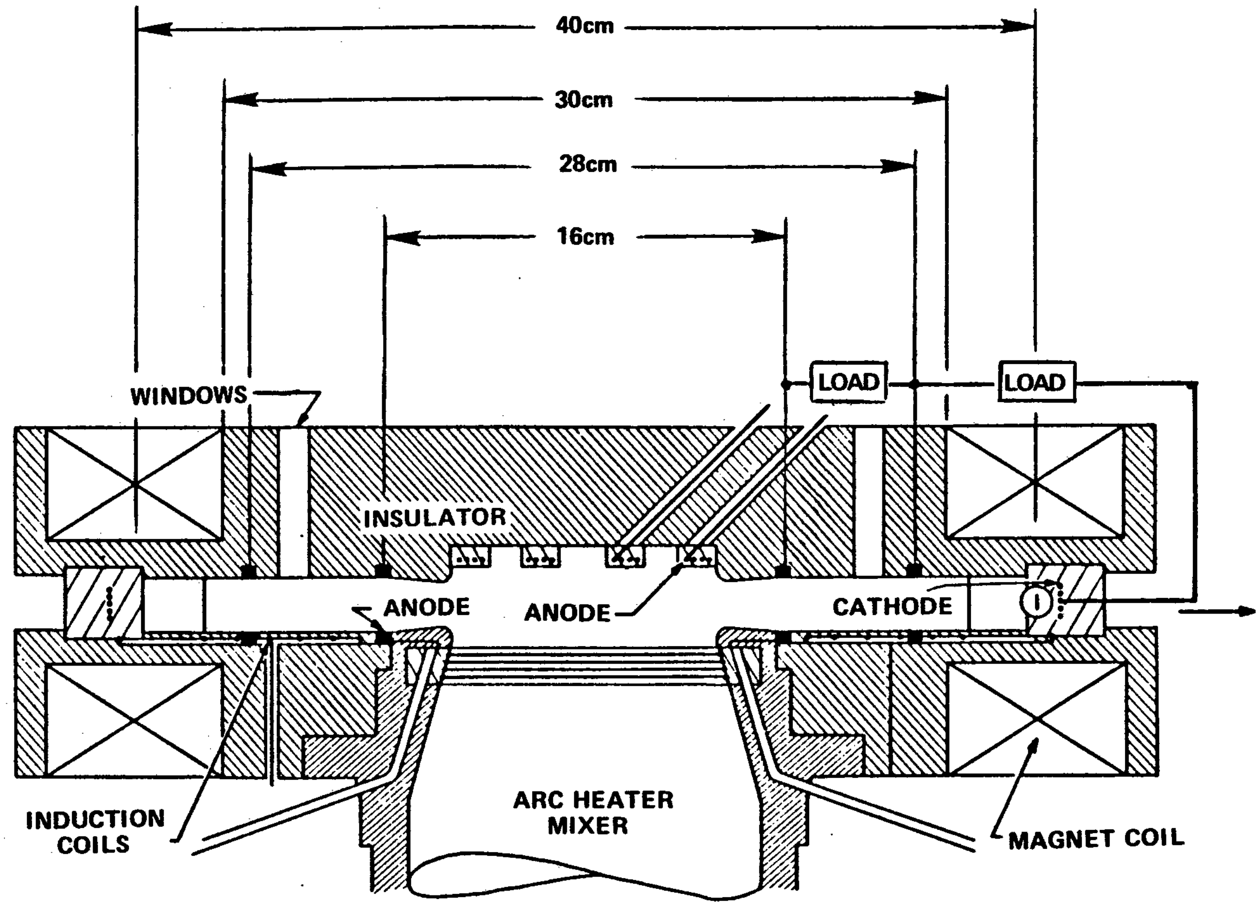


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Figure 5-12. Test Disk Generator Configuration with Insulating Nozzle Walls, Pre-Ionization Electrodes and Annular Windows Used for Fast Photography

Personnel/Schedule

During testing operations, including test setup and termination, the personnel involved will include R. Holman, Prof. J. Louis, J. Brindza, B. Pierce, a full time test engineer and supporting technicians. Estimated duration of the anticipated activities are presented in Figure 5-8.

5.1.2 Analytical Investigations

The initial efforts of Task 2 will include a number of analytical investigations using the verified disk MHD calculational model and test system power generator model. The principal efforts will be targeted at understanding the characteristics of the disk plasma and power generation relationships and defining stable operating maps and design data for test design and operating conditions. Before these analytical investigations can be conducted, the calculational model for the Task 2 experiment disk MHD generator must be defined and verified by plasma experimental data with hydrogen and cesium conducted at MIT in the shock tunnel (Task 1220).

The supporting analytical subtasks are:

- development of a plasma property calculational model based on the results of plasma property experiments

- development of computer design and performance calculational models for the disk generator driven by hydrogen based on results of and verified by the MIT shock tunnel experiments of Task 1220

- development of seed mixing models and design criteria for verifying adequate seed control and mixing to guide design and operation.

5.1.3 Auxiliary Component Development

The Task 1 effort identified several areas for component and auxiliary systems development where analytical, engineering design and/or testing are needed. These are:

- Space System Environment Impacts - Disk Generator Design and Fabrication
- Space Operations of Disk Generator Electrical-Thermal Isolation
- Power Conditioning and Interfacing
- Seed Control and Mixing

Approaches to addressing and resolving these development issues are presented below.

5.1.3.1 Design and Fabrication

The status of engineering technology for identified elements of the disk MHD generator was presented in Figure 4-3. For those elements noted in Figure 5-13 that require development and testing, a description of the approach to be employed is provided. These elements are:

- Ceramic Attachment Method (liner to structural material)
- Electrical-Thermal Insulation
- Coolant and Electrode Connections/Fabrication
- Structural Materials in Space Environment

CERAMIC ATTACHMENT METHOD

<u>Problem</u>

The ceramic material used to insulate and protect the generator housing from the plasma must be attached to the housing in such a manner to accommodate differential thermal expansion between the structure and ceramic as well as electrically isolate the structure for up to 20 kV potentials. The system must be stable for 10 years at approximately 300 K and withstand 25 cycles from 1000 to 1300 K in 4 s with a 300 to 400 K temperature difference between the structure and ceramic. No material may be dislodged by the high velocity plasma.

Problems	State-of-the-Art: Available	Being Developed	Requires Development
• Attachment method of ceramic liner to structural material.	X		Standard methods require refinement and testing.
• Thermally and electrically insulating ceramic (between NPB and structure).	X		Electrical insulating coating on structural metal demonstration in space environment.
• Select composite materials for space environment.	X	X	Material coating and endurance in space environment
• Cooled electrode fabrication.	X		Requires refinement.
• Electrode material to conductor material joint.			Fabricate and demonstrate.
• Titanium coating	X	X	Fabricate and demonstrate may require Phase II testing.

Figure 5-13. Status of Design and Fabrication Development

Approach

A number of ceramic to metal attachment methods will be evaluated based upon meeting the defined system design requirements. These designs will be subjected to a formal design review and evaluation team for selection of the two most promising designs for testing.

An initial screening test will be conducted in which the attachment system will be subjected to the calculated loads at ambient conditions. Then the system will be loaded at the highest and lowest temperatures attainable in state-of-the-art testing machines. A third test will verify the capability to accommodate the number of mission temperature cycles using the maximum and minimum design temperatures. After cycling, the attachment system will be loaded at the highest and lowest attainable temperatures. The most promising system will then be proof tested.

The proof test will be designed to subject the selected attachment system to twice the number of mission cycles and duplicate as closely as possible the temperature levels, transients, and plasma velocity using cryogenic cooling and an inert plasma torch arc heater.

The cooling and heating equipment employed will be the same as that to be used in WBS-1250, EXPERIMENTAL HYDROGEN DRIVEN DISK GENERATOR.

The ceramic to structure attachment system selected from these tests will be verified in the experimental disk generator to be used in WBS-1250.

ELECTRICALLY INSULATING COOLANT CONNECTOR

Problem

Wherever hydrogen is used internally to cool an electric current carrying line, the hydrogen source must be electrically insulated from the line. An example is the connection between the hydrogen cooling supply and the anode and cathode current collection system. This insulating connector must be developed.

Approach

The insulating material may be connected to the current carrier either through permanent bonding or mechanically. Permanent bonding, by a metallurgical process similar to welding or brazing, is preferred. However, depending on the materials used, a mechanical joint similar to a screwed fitting may be required. A candidate material for the MHD channel insulator is boron nitride due to its high electrical resistivity, thermal conductivity and workability.

The joint will be designed, team reviewed and subjected to load, shock and vibration testing based on mission requirements. The developed joint will be verified in the experimental disk generator test under WBS-1250.

RESOLUTION OF ENGINEERING PROBLEMS

Problem

During component testing, conceptual design evolution, and definition, some areas (supports, connections, materials and interfaces) of the design are expected to be identified as possible cost reduction, performance improvement or problem areas. Problems may be identified where vibration or thermal cycling and long term space environment challenge design approaches. Proof tests will be defined where analyses cannot resolve the questions. Allowance for these efforts requires some contingency in the development program. However, assessments during Task 1 have not included estimating these potential requirements.

Approach

At this point, problems are considered to be of an engineering nature and do not effect the power system feasibility. The results of engineering analyses will identify the need for experimental verification. Any tests required will be defined and detailed for the Phase II program plan. Tests will not be performed until required in conjunction with the prototype design effort.

5.1.4 Work Breakdown Structure and Schedule

For Task 2, Subsystem/Component Development, Analysis and Testing, an intense 24 month program is proposed. The general approach for Task 2 is shown in Figure 5-14. Consistent with the sequence of activities shown in this figure, the Task 2 Work Breakdown Structure is devised so that an on-going analysis task mutually complements a series of disk generator related experiments and tests. These experiments culminate with the fabrication, assembly and test of a multimegawatt experimental disk generator. The generator will be tested with seeded hydrogen heated by a plasma torch, to conclusively demonstrate operational stability and high enthalpy extraction capability.

The Task 2 WBS and schedule are shown on Figure 5-15. Six major technical subtasks are defined. Four of these subtasks cover engineering development and tests of experimental disk generators and related components. A system analysis subtask (WBS 1210) provides a concurrent analytical effort that resolves specific technical issues and interacts with all of the development/test efforts. The Phase I feasibility assessment will be completed and documented under WBS 1260. This subtask will provide for the synthesis of all of the other efforts from Tasks 1 and 2 and will include the preparation of an updated MMW MHD power system conceptual design.

As can be seen from Figure 5-14 and the schedule of Figure 5-15, Task 2 is devised so that the experimental effort culminates in a test program with a

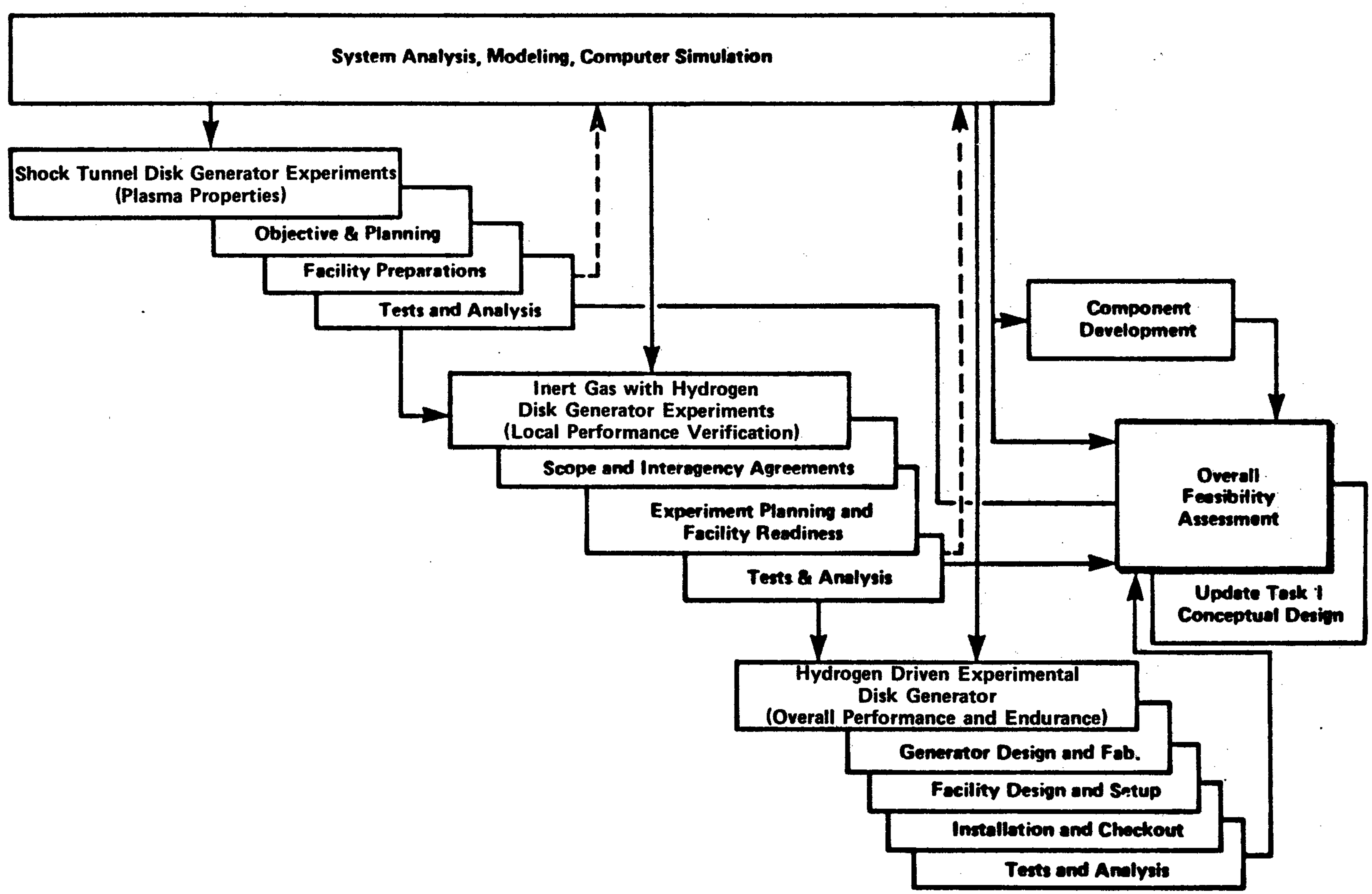
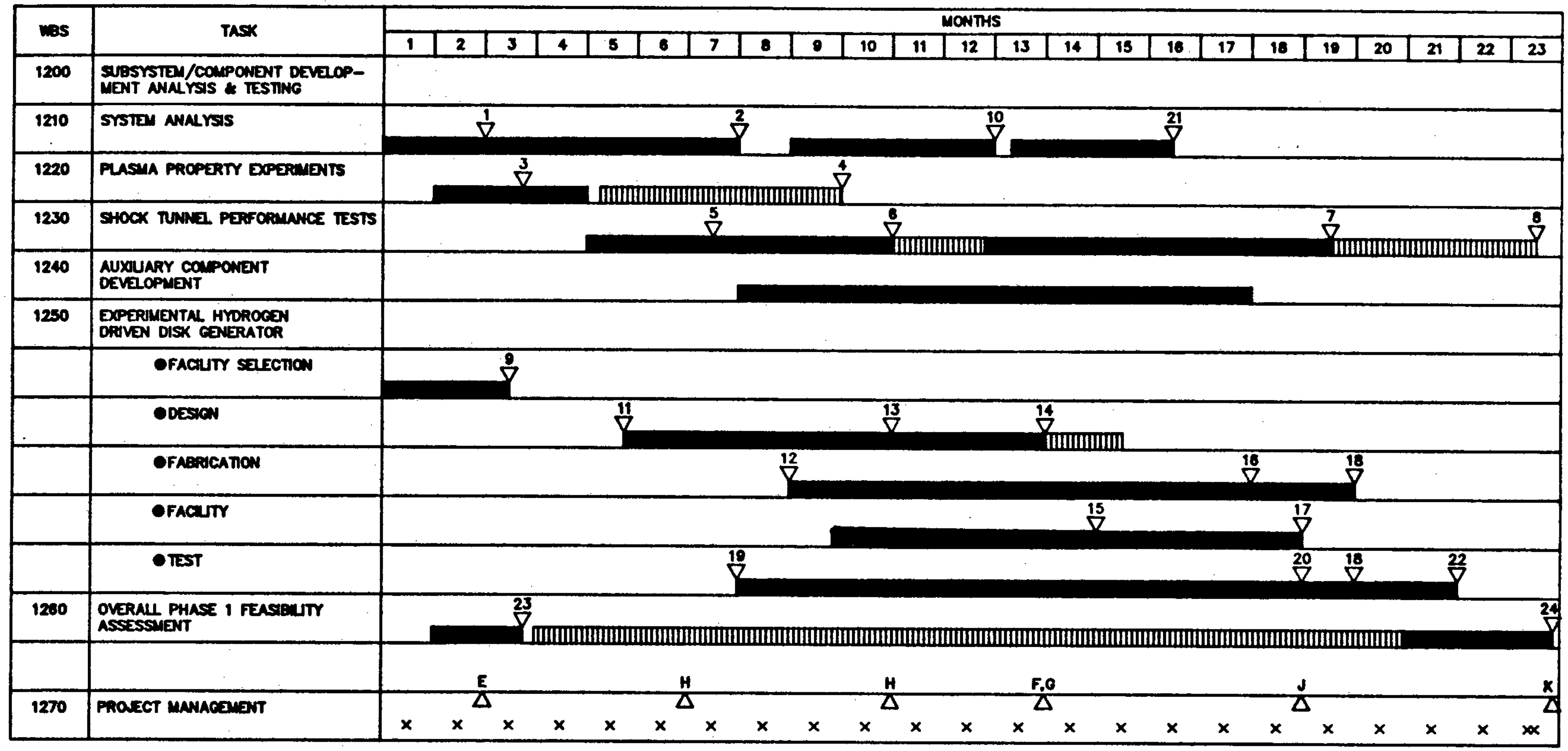


Figure 5-14. Task 2 General Approach



MILESTONE SCHEDULE & STATUS REPORT

TASK 2 KEY EVENT

1. Analysis plan issued
2. Issue guidance to shock tunnel performance tests
3. Plasma conductivity demonstrated and other plasma measurements initiated
4. Topical report draft on plasma properties
5. Nonequilibrium performance demonstrated
6. Generator low B field performance measurements completed
7. Generator high B field performance measurements completed (with reversed field)
8. Generator performance data report
9. Facility review and recommendation completed
10. Model update incorporating shock tunnel test results
11. Initiate endurance experimental disk generator design
12. Order long lead materials
13. Prelimina:
14. Endurance generator design complete
15. Plasma torch procurement complete
16. Endurance generator fab/assembly complete
17. Test facility modifications complete
18. Test article installed and checked out
19. Preliminary test plan issued
20. Final test plan
21. Analysis guidance to test plan submitted
22. Endurance disk generator tests complete
23. Preliminary 100 MWe space system specification
24. o Updated 100 MWe conceptual design
    o Final Phase 1 system specification
    o Phase 2 draft program plan issued

DELIVERABLE DOCUMENTATION

Deliverable Item	Description	Applicable WBS
TASK 2		
E	Detailed Test Plan (for each test or test series)	1270
F	Test Component/Subsystem Design Report	1270
G	Test Component/Subsystem Assembly and Installation Drawings	1270
H	Preliminary Test Reports	1270
J	Topical Reports of Analytical Studies	1270
K	Draft Final Technical Report	1270
X	As Specified by URSC*	

*Uniform Reporting System for Contractors

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Figure 5-15. WBS and Schedule for Task 2 nominally 10 MW (thermal input), hydrogen driven disk generator. This device, which will be designed, built and tested under WBS 1250, is intended to verify the predicted performance, stability and operating efficiency of the concept. Tests with this experimental generator will, more than any other single aspect of the program, confirm the Phase I level feasibility assessment.

Before the experimental hydrogen disk generator is designed and built, a set of disk generator experiments is to be performed at MIT using the existing shock tube disk generator test facilities. The first set of these experiments, under WBS 1220, is designed so as to determine plasma properties in the range of pressures, temperatures and Hall coefficients of interest. The second set of experiments, which are under WBS 1230, also use the MIT shock tube facility. These experiments, however, are aimed at determination of disk generator performance using a mixture of argon and hydrogen. Three physical regions of the generator are to be examined: the conventional section located in the inner base of the magnet, a section located between the coils, and a section located just downstream of the outer diameter of the coils.

After these experiments are successfully completed, the design and fabrication of the multimegawatt experimental disk generator can proceed with confidence. These efforts, with related facility modifications, assembly, checkout and testing, are under WBS 1250.

DETAILED WORK STATEMENTS

A set of detailed Work Statements for Task 2 follows consistent with the WBS and schedule shown in Figure 5-15 and written to the third level (subtask) WBS.

WBS 1210 - SYSTEM ANALYSIS

<u>Objective</u>: To perform well defined system analyses of both steady state and dynamic performance aspects of the nuclear driven disk MHD generator system

and to provide analytic and design guidance for definition of experiments planned under other subtasks.

Approach: Evaluate existing analytical models of disk generator and NERVA reactor performance, and determine where gaps occur in assembly of an analytical system consisting of the reactor, MHD generator, and other subsystems. Modify and refine the existing models and create new models where required to synthesize an overall power system mathematical model. Mechanize this model on appropriate digital (e.g., CRAY) or hybrid computers, checkout the codes and initiate design related studies. Analyze the results from these early studies and provide guidance to the shock tube experiments scheduled at MIT. Obtain feedback from these experiments and modify/refine the models as needed.

Perform additional studies that simulate the planned test configuration for the multimegawatt hydrogen driven disk generator at CDIF. From these studies, provide design and test guidance to WBS 1250. Obtain feedback from the test results at CDIF and further refine the model parameters as appropriate.

Use the refined model following the CDIF test results to perform additional analysis that guides the preparation of the updated conceptual design of the 100 MW_e space-based power system.

Anticipated Problems/Difficulties: None

Principles/Techniques to be Applied: Prepare an overall analysis plan at the outset of this subtask to guide the effort throughout. Use existing computer codes and facilities upgraded as needed. For newly created model features, incorporate appropriate level of computational tools consistent with economy and timeliness.

WBS 1220 - PLASMA PROPERTY EXPERIMENTS

Objectives: To gain a good, experimentally based understanding of the properties of the type of plasma expected for the nuclear driven MMW disk generator.

Approach: Use the existing shock tube disk MHD generator facility at MIT for these experiments. Determine required experimental measurements for plasma properties and obtain additional instrumentation if required. Modify the facility as needed and as indicated by an overall test plan for this subtask. Perform the experiments with seeded inert gas (argon) with sufficient hydrogen added to dominate the plasma behavior. Analyze the data from the experiments and determine the appropriate plasma properties in the range of pressures, temperatures and Hall coefficients of interest.

Anticipated Problems/Difficulties: None

Principles/Techniques to be Applied: Formal "design of experiments" techniques including statistical design, such as factorial design, so as to permit a maximum amount of information to be gained from a minimum number of experiments.

WBS 1230 - HYDROGEN/INERT GAS SHOCK TUBE PERFORMANCE TEST

Objective: To obtain experimental verification of the predicted performance of the disk generator for three distinct regions of the generator.

Approach: Use the MIT shock tube facility to conduct a set of short duration experiments that provide measurements of MHD performance in three sections of the disk generator. First evaluate the performance in the conventional section of the generator located in the inner base of the magnet. Next evaluate the performance in a section located between the coils, and third, evaluate a section located just downstream of the outer diameter of the coils. For these experiments, place special purpose electrodes in the appropriate locations for each of these sections of the shock tube and use the voltage and current measurements obtained from these electrodes as the primary performance indicator. Also determine other key experimental measurements needed from these tests, and instrument the shock tube facility accordingly. Analyze the data from these experiments and use in conjunction with the shock wave calculated power input to the generator to assess the relative enthalpy extraction from each section.

Anticipated Problems/Difficulties: None

Principles/Techniques to be Applied: Use a well defined test plan to guide the preparation, conduct and evaluation of these experiments. Make use of statistical design techniques to maximize the basic and inferred information from these experiments. Use an appropriate mole fraction of hydrogen (5 to 15%) in the argon working fluid so as to permit the electron collision mechanisms in the plasma under nonequilibrium conditions to be dominated by the hydrogen.

WBS 1240 - AUXILIARY COMPONENT DEVELOPMENT

Objectives: Pursue design and engineering development activities on several key components in the system where significant uncertainties have been identified. Electrode design configuration and materials selection, seed mixing in the hydrogen stream and power conditioning interface definitions between the MHD generator/weapons system represent areas of concern.

Approach:

Seed Mixing: Evaluate the characteristics of seed feed variations and control requirements in computer models and compare to capability of seed feed and mixing system concepts. Identify suitability of electric heating of pressurized seed vapor and metering control for feed and mixing of 0.015 molar percent (1.5×10^{-4} mole fraction) cesium into heated hydrogen at 19 atmospheres pressure. Correlate results from MIT shock tube experiments with analytical model and verify that seed feed can meet predicted requirements. Define component test requirements, specify and design test, and make test predictions for experimental disk tests which will be conducted under WBS 1250.

Electrode Development: Evaluate state-of-the-art in electrode technology for disk generators and compare to the particular requirements on electrodes imposed by this application. Identify suitable materials of construction and fabricate experimental electrode configurations predicated on the Task 1 disk generator conceptual designs. Investigate test requirements and determine whether suitable component testing is required under this subtask. Specify test requirements unique to electrodes that are to be performed with the experimental disk generator under WBS 1250.

Power Conditioning: Use the interface requirements and definition between the burst power system and the SDI weapons platform to specify a set of power conditioning development efforts. From the system analysis subtask (WBS 1210), obtain estimates of the expected waveforms, duty cycle and noise likely to be superimposed on the output of the power conditioning and the noise present on the output of the disk generator terminals. Determine the impact of these characteristics on power conditioning circuits for the mission systems and magnet power supply.

Perform literature reviews of related programs to evaluate the long term effects of the space environment and power system induced environment (e.g., nuclear radiation and magnetic fields) on power conditioning components and insulating materials. Evaluate specific circuit configurations for magnet power conditioning and determine the feasibility of building a scaled version of this circuit for tests with the experimental disk generator under WBS 1250.

Evaluate the relative merits of coaxial power transmission lines and conventional cable systems by considering weight savings, dual use of hydrogen piping, and combining lines with the system structure.

Anticipated Problems/Difficulties: Control of feed and measurements with very small flow rates and sensitivity required may involve sophisticated measuring equipment such as continuous gas chromatography, but this is not considered serious.

Principles/Techniques to be Applied: Use analytical design and launch type component experiments to define suitable concept approaches. Identify the system that can best meet requirements. Demonstrate the system at required performance.

WBS 1250 - EXPERIMENTAL HYDROGEN DRIVEN DISK GENERATOR

Objective: To demonstrate, at the multimegawatt level, the high performance potential of hydrogen driven disk generators. More specifically, to build and test an experimental disk generator for at least 100 s continuously and during these tests to obtain generator power density that verifies that the 100 MW_e disk would attain enthalpy extractions exceeding 50%.

Approach: When Task 2 is initiated, a detailed facility modification/cost review will be completed, and a site recommendation will be presented. Prepare a detailed plan for testing of the MMW experimental generator and use the ongoing results from WBS 1210, WBS 1220 and WBS 1230 as guidance in preparing this plan. Prepare the preliminary design of the disk generator and identify overall test facility requirements and needed modifications to the CDIF to accommodate this test.

Prepare detailed design of the MMW experimental disk generator and initiate procurement of long lead materials. Finalize the design, issue an RFQ for fabrication, and evaluate "Make or Buy" orders for major generator components: magnet, disk, structure, electrodes, and electrical interconnecting equipment. Write specification for component acceptance testing and monitor these tests at fabricators' facilities.

Initiate design and procurement activities at CDIF based on the facility requirements document. Include the cryogenic system for magnet, magnet power supply (if self-excited magnet is not used), power supply and substation alteration for the plasma torch arc heater, provisions for resistive load for MHD generator electrical output, generator test stand, supplies of liquid hydrogen, cesium seed injection system, plasma torch equipment to heat hydrogen, pumping equipment, and equipment for handling/venting of generator plasma exhaust.

Complete the test facility design activities requiring facility modifications including unique control and instrumentation requirements. Assemble the MMW experimental generator and ship to CDIF for installation. Install the generator onto the test stand and integrate it with the plasma torch. Integrate the test article with structural, electrical and thermal facility interfaces and perform functional checkouts.

Verify facility and test article readiness and conduct ongoing safety reviews and approvals. Prepare final operational and safety documentation and obtain approvals for power testing.

Conduct a series of MHD power tests in accordance with the final overall test plan. Evaluate the results, analyze performance and provide feedback to WBS 1210 for reconciliation with generator design performance models.

Anticipated Problems/Difficulties: As evidenced by the scope of this subtask, and in the context of the RFP schedular/budget constraints, successful completion of this subtask has little or no provision for accommodating setbacks in design, procurement, fabrication, installation, checkout or test.

Principles/Techniques to be Applied: To ensure that the experimental disk generator can be designed, built and tested with required facility constraints within the RFP schedule and budget, it is vital that this subtask be driven by an objective to attain simplicity in test article and facility features. This emphasis, coupled with safety requirements, will be applied throughout the performance of the subtask.

WBS 1260 - OVERALL PHASE I FEASIBILITY ASSESSMENT

Objective: To perform the Phase I feasibility assessment of the nuclear disk generator concept for space-based applications and recommended scope of Phase 2 of the program. Phase II will represent the final feasibility assessment.

Approach: Early in Task 2, initiate a power system specification with major input from Boeing for the 100 MW_e space application design concept. Base this specification on the conceptual design prepared in Task 1. For purposes of this specification, identify, with SDIO concurrence, one or more specific weapon systems as a basis for defining the specific and detailed power system/space platform interfaces in this specification.

Use the 100 MW_e System Specification as a "living" document throughout Task 2. Incorporate evolving requirements that relate to space environment operational modes and mission system demands. Use the pertinent results of other design studies sponsored by SDIO/DOE on MMW gas-cooled (NERVA derivative type) reactors as they pertain to this power system. This particular activity will permit this contract to take advantage of the work on MMW gas-cooled reactors with a modest commitment of funds from this contract. In effect, the bulk of the nuclear reactor related issues from Task 1 (WBS 1120) will be dealt with effectively and economically during Task 2 as part of this subtask (WBS 1260).

From the system analysis results (WBS 1210), all of the results of the experimental efforts in Task 2 (WBS 1220, 1230, 1240 and 1250) and the 100 MW_e System Specification (WBS 1260), prepare the updated system conceptual design. Use the design concept from Task 1 (WBS 1130) as the basis for this updated design. When the design update is complete, incorporate it into the System Specification.

Use all of the results discussed above to prepare a Phase II recommended program for the design, fabrication and testing of a full 100 MW_e ground prototype system to be driven by a NERVA derivative reactor.

Anticipated Problems/Difficulties: SDIO/DOE-PETC intends to keep this procurement unclassified while SDIO/DOE-NE has the MMW reactor programs in progress already on a classified basis. Under these conditions, there would be major difficulties in being able to perform the scope of this subtask as discussed herein.

Principles/Techniques to be Applied: SDIO and DOE need to reconcile their present position on classification of various elements of SDI space power programs. When that is done, the approach outlined in this proposal, especially in this subtask, can readily lead to a thorough Phase I Feasibility Assessment and recommended Phase II program.

WBS 1270 - PROJECT MANAGEMENT

Objective: To ensure effective management of the project via schedular and cost control, technical direction of Westinghouse and subcontractor activities, timely submittal of deliverable items and frequent customer communication.

Approach: Use appropriate Westinghouse project management techniques and practices tailored to the needs of this program. Prepare reports and submit to DOE in accordance with the Reporting Requirements Checklist.

Anticipated Problems/Difficulties: None.

Principles/Techniques to be Applied: Use techniques and tools such as Westinghouse Integrated Management and Control System (IMACS), Action Commitment Expediting System (ACES), Work Authorization and Subcontractor Management system. These systems are described in Section 5.2.5 of this report.

5.2 Management and Personnel

The MHD Feasibility Assessment project organization will be based at the Westinghouse AESD Site located at Large, PA. AESD's scope and experience include most of the MHD programs performed by Westinghouse over the last decade and prior work concerning disk MHD generator concepts. All Westinghouse advanced reactor work has also been carried out within AESD, including gas-cooled reactor development beginning with NERVA. Development of the design concepts and examination of applications of this gas-cooled NERVA derivative reactor technology have continued over the past decade. Recently, in both Corporate-funded and contract programs, we have been examining the application of the NERVA derivative reactor technology to SDI space-based multimegawatt power systems. The concept requires the integration of the disk MHD generator and NERVA derivative reactor technologies to form the MHD power system for space-based SDI applications. AESD personnel who have prior experience and a continuing involvement in these two technologies will be key in Task 2 of the MHD Feasibility Assessment program. Task 2 will be carried out with efficiency and a high level of productivity by means of the following approach:

- Using key personnel with directly related MHD and reactor technology experience.

- Integrating efforts, where appropriate, with AESD's other space-based multimegawatt programs.

- Providing the necessary Division and Corporate resources.

- Ensuring timely and cost-effective use of support personnel and the availability of backup personnel via the Westinghouse matrix organization

- Appointing a Project Manager whose previous managerial technical experience matches the program requirements.

- Forming a Senior Technical Review Board composed of senior technical managers who are well versed in MHD and reactor technology; they will be a valuable resource to the Project Manager and will ensure that technological opportunities are identified and exploited

- Using in-place, proven project management procedures tailored to the scope and objectives of the proposed program to control the work effort, costs and schedule

- Ensuring high level Westinghouse management visibility via regularly scheduled internal program reviews

The following sections describe the Project Manager's qualifications, interfaces with the Westinghouse Corporate structure, the proposed project organization, and the teaming arrangements.

5.2.1 Performing Project Manager

We have selected Mr. B. L. Pierce, currently Manager of Emerging Systems Projects, as the Westinghouse Project Manager for Task 2 of the MHD Feasibility Assessment Program. He was chosen based on the following considerations:

- The Task 2 statement of work content and the special contract requirements of the program

- His current project management responsibilities for AESD's classified and unclassified programs for space-based multimegawatt SDI power systems.

- His prior record as project manager and principal investigator for prior DOE contracts involving multimegawatt NDR/MHD and NDR/Brayton power systems.

- His detailed knowledge of system design, modeling, analysis and testing of high temperature heat exchanges and energy conversion systems.

- His previous successful working and personal relationships with the key Westinghouse personnel and team members

Mr. B. L. Pierce will have complete authority to command the required resources and to manage the program within the limits of funding and schedules to achieve the contract objectives. As Project Manager, Mr. Pierce will be required to provide frequent technical and programmatic reviews to senior Westinghouse management. He will also be responsibile for integrating the Task 2 effort with other Westinghouse AESD space-based multimegawatt programs with regard to SDI application requirements and NERVA Derivative Reactor technology.

5.2.2 Project Organization

During Task 1, the analysis, design and characteristics of the disk MHD generator subsystem were the determining factors in the definition of the total MHD power system conceptual design and identification of the key technical issues.

However, Task 2 of the Phase I effort, with the overall goal of demonstrating the MHD Power System control feasibility, requires:

- System/Subsystem/Component Development, Analyses and Testing to resolve key technical issues and validate high interaction MHD performance

- Test Article Design and Fabrication

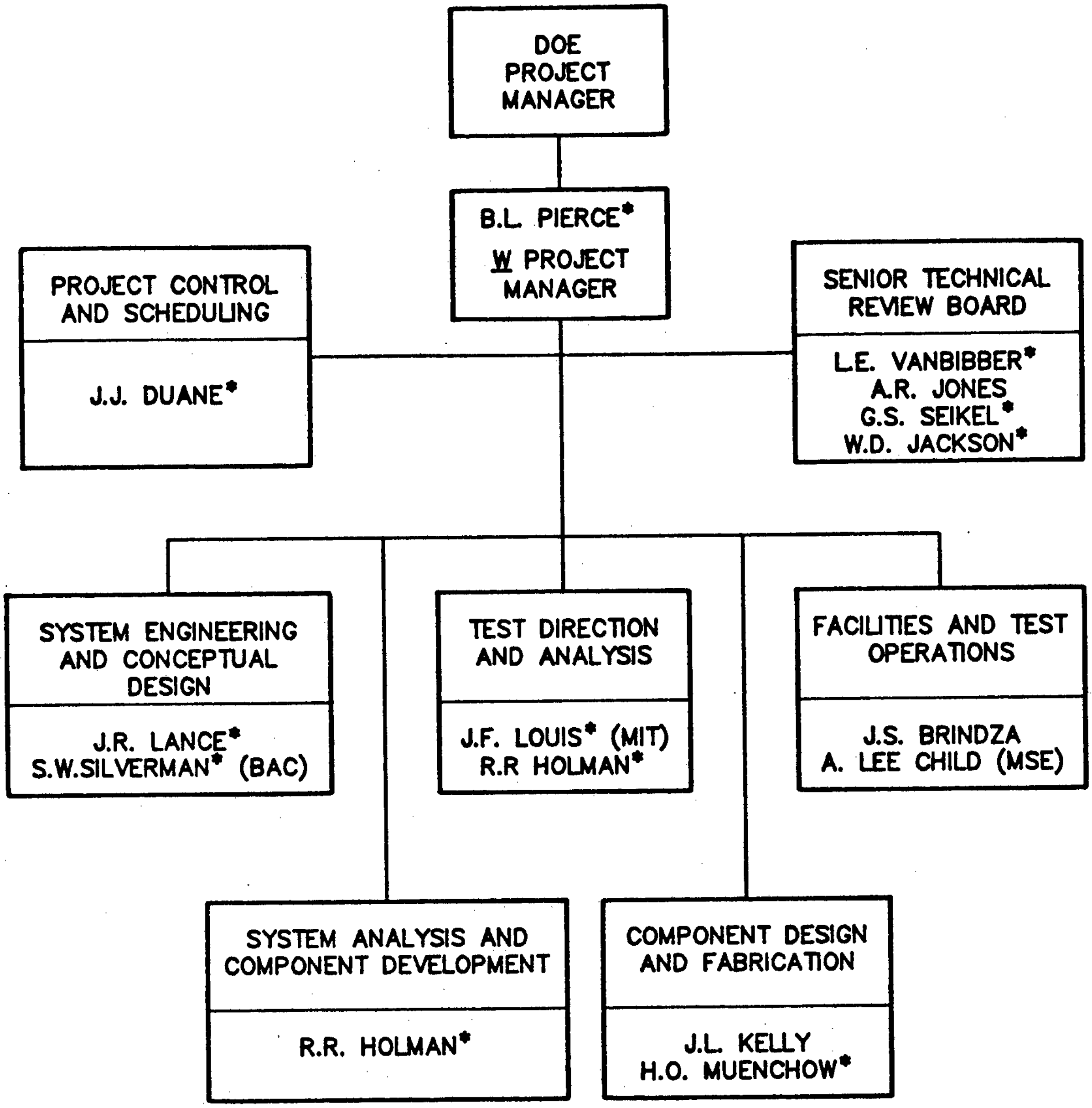
- Revision or modification, as necessary, of the MHD Power System Conceptual Design

The Task 2 organization, illustrated in Figure 5-16, provides continuity with Task 1 in that the same key personnel are involved but in roles that are appropriate for the development, analysis, and testing activities and revision of the MHD power system conceptual design.

All of the Task 1 contributors and key personnel (except for one retiree) have been retained as indicated in Figure 5-16. Mr. B. L. Pierce, because of his prior related management and technical experience and his current focus on SDI multimegawatt power systems will serve as the Westinghouse Project Manager for Task 2. Mr. L. E. Van Bibber, who served as the Task 1 Project Manager, has been assigned project management responsibilities to concentrate on DOE/PETC funded terrestrial MHD and clean coal technology contracts. However, he will serve on the Senior Technical Review Board during Task 2 to contribute his prior Task 1 experience and facilitate the transition to the Task 2 effort.

A Component Design and Fabrication activity has been added to the Task 2 organiztaion. Mr. J. L. Kelly, Westinghouse AESD's Manager of Equipment Design, will be responsible for this activity. He will be supported by Mr. H. O. Muenchow who has contributed to the Task 1 major component conceptual design. Mr. Kelly has extensive experience in the design of developmental hardware and in Task 2 he will be responsible for the design and fabrication of all major experimental hardware items performed by Westinghouse and its subcontractors. He will also be responsible for supporting internal Westinghouse design reviews and DOE critical design reviews.

During Task 2, R. Holman/Dr. J. F. Louis will be responsible for establishing test objectives, test direction, and analyses of experimental data. Mr. J. S. Brindza, with the input of the other team members, will be the technical point of contact for the preparation of the experimental procedures documents. He will also oversee the required facility modifications and the conduct of test operations to ensure compliance with planned experimental procedures.



SUPPORTING ACTIVITIES AND PERSONNEL:

- MATERIALS – A. BOLTAX/R.L. AMMON*
- SYSTEM ANALYSIS – J.P. HANSON*/F.E. BERNARD*
- MAGNETS – P. MARSTEN* (MIT)

* – CONTRIBUTORS TO TASK 1

Figure 5-16. Westinghouse/Team Organization Structure for Task 2 – Subsystem/Component Development, Analysis, and Testing

Mr. J. R.Lance will be responsible for Task 2 revisions and refinements of the 100 MW_e/500 s MHD power system conceptual design and the specification and interface documents. He will be supported by Mr. S. W. Silverman of Boeing. Mr. Silverman will contribute to the definition of interfaces, design integration of the proposed MHD power system concept with the weapon system and the space platform, and assessment of the overall system effects caused by the operation of the MHD Power System.

R. R. Holman will be responsible for system analysis design and engineering development activities for the 100 MW_e/500 s power system concept including the resolution of key technical issues. He will also continue to provide support in the area of NERVA Derivative Reactor technology. Dr. J. P. Hanson and Ms. F. E. Bernard will provide support in the areas of system modeling, trade off studies, and computer code development.

Materials evaluations will be performed primarily by Mr. R. L. Ammon in the area of structural materials and Mr. A. Boltax in the nuclear fuel area. Other specialists in the AESD Materials Technology Department will be consulted as needed.

Mr. J. J. Duane will provide project cost and scheduling control support to the Project Manager.

The Senior Technical Review Board, consisting of Mr. L. E. Van Bibber (Westinghouse AESD), Mr. A. R. Jones (Westinghouse R&D), Mr. Seikel (Seitec, Inc.) and Dr. Jackson (HMJ Corporation), will provide a strong advisory resource for Mr. B. L. Pierce, the Project Manager, and will ensure that technological opportunities are identified and fully exploited. The qualifications of the review board members are presented in Section 5.2.4.

5.2.3 Project Personnel

All of the qualifications the key personnel on the Westinghouse Team and their responsibilities for Task 2 are identified in this section. Key personnel are defined as those personnel who meet one or both of the following criteria:

- Personnel who have unique capabilities or direct experience related to the Task 2 scope of work

- Personnel who, in terms of labor hours, will account for a significant contribution to the proposed effort

The Task 2 project personnel meeting both of the above criteria and their areas of contribution are listed in Figure 5-16. Westinghouse and the teaming organizations have, in many areas, more than one person with related experience who can perform specific Task 2 subtasks. In addition, AESD is organized in matrix form to provide flexibility and rapid alignment of qualified personnel with new or changing project requirements. Our resources include backup personnel who can replace key persons, if necessary, and qualified technical support personnel. Figure 5-17 presents the key position responsibilities and the rationale for selecting the key personnel. Summary qualifications of support personnel that we will use to perform specialized tasks are provided immediately following the key personnel qualifications.

5.2.4 Senior Technical Review Board

During Task 1 we formed a Senior Technical Review Board that will continue to provide a strong advisory resource for the Project Manager and the Team through Task 2 of the project. The personnel on the Review Board include Mr. L. E. Van Bibber, Mr. A. R. Jones, Mr. G. S. Seikel, and Dr. W. D. Jackson. Mr. L. E. Van Bibber was the Westinghouse project manager during Task 1 of the MHD Feasibility Assessment program. His current AESD assignment is project management of DOE/PETC funded terrestrial MHD and Clean Coal Technology contracts. Mr. Van Bibber's service on the Technical Review Board will make his Task 1 experience directly available to the project team and the Task 2 Project Manager. Mr. A. R. Jones was

KEY PERSON - B. L. PIERCE - PROJECT MANAGER
Westinghouse Advanced Energy Systems Division

RESPONSIBILITIES:

- Receive and execute, on behalf of Westinghouse, technical directions issued by the DOE Project Manager within the terms and conditions of the contract
- Provide management direction of the MHD/Feasibility Assessment program team to assure attainment of objectives within budget and schedule constraints
- Develop and implement work plans
- Coordinate efforts of Westinghouse team members, subcontractors, and consultants
- Chair technical and managerial meetings
- Provide a single point of contact for all oral and written communications with the DOE/PETC Project Manager
- Ensure compliance with all contractual reporting and deliverable requirements

RATIONALE FOR SELECTION:

- Has current Westinghouse project management responsibilities for multimegawatt SDI power system activities.
- Extensive experience as principal investigator for DOE funded contracts involving the system design and analysis of NDR/MHD and NDR/Brayton space power systems.
- Detailed knowledge of system design modeling and analysis of energy conversion systems and the thermal design of high temperature components and heat exchangers.
- Thorough knowledge of the NERVA program with responsibilities for development of computer codes and simulation models for thermal, fluid and nuclear transients.
- DOE-Q and DOD Secret security clearances
- B.S. and M.S. in Mechanical Engineering with 28 years of experience in advanced energy conversion and aerospace technologies.

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 1)

KEY PERSON - J. F. LOUIS - DISK MHD GENERATOR DESIGN AND ANALYSIS
(Department of Aeronautics and Astronautics, MIT)

RESPONSIBILITIES:

- Assist in disk MHD generator analysis and concept design
- Identify and resolve key technical issues for the disk MHD generator subsystem
- Provide input to the experimental plan for shock tube driven disk MHD generator experiments and the electric arc driven disk MHD generator endurance tests
- Conduct shock tube driven disk MHD generator experiments, analyze and report results
- Provide technical direction of arc driven disk MHD generator endurance tests and assist in the analysis and reporting of results

RATIONALE FOR SELECTION

- Twenty eight years of total experience with more than 25 years of experience in the field of magnetohydrodynamics
- Conceived and built the first alkali metal shock tube for studies of closed cycle MHD in a disk generator
- Extended studies of disk MHD generators driven by molecular gases including hydrogen
- Directed pioneering work on the combustion driven Mark II MHD generator at AVCO-Everett Research Laboratory
- Recognized worldwide as the leading investigator of disk MHD generators
- Published more than 100 articles and papers on MHD generator design and mechanics
- Professor, Massachusetts Institute of Technology, from 1972 to present
- Ph.D., Cambridge University, England
- Ingenieur Civil Mecanicien et Electricien, University of Brussels, Belgium

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 2)

KEY PERSON - R. R. HOLMAN - SYSTEM ANALYSIS AND COMPONENT DEVELOPMENT
Westinghouse Advanced Energy Systems Division

RESPONSIBILITIES:

- Direct auxiliary component design and development activities
- Direct system analysis and tradeoff studies
- Identify and resolve key technical issues and contribute to the experimental plan
- Assist in evaluating experimental and test data and formulating conclusions
- Evaluate experimental results against system computer codes to validate analytical models and to verify achievement of experimental objectives
- Assess impacts on nuclear subsystem conceptual design and make any needed design changes

RATIONALE FOR SELECTION

- Experience in design, analysis, and testing of advanced systems for nuclear space power and propulsion spans 3 decades
- Has approximately 16 years of experience in the analysis and design of MHD generators and power plants
- Industrial staff member assigned to the Los Alamos Scientific Laboratory nuclear rocket development team with contributions to the successful KIWI reactor core lateral support design and on-line reactor test monitoring procedures
- Managed fission and fusion nuclear subsystem design efforts
- B.S. and M.S. in Aeronautical Engineering, University of Kansas

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 3)

KEY PERSON - JOSEPH R. LANCE - SYSTEM ENGINEERING AND CONCEPTUAL DESIGN
Westinghouse Advanced Energy Systems Division

RESPONSIBILITIES:

- Prepare the conceptual design description and drawings of the complete MHD power system
- Specify the MHD power system and subsystem interfaces and design/performance requirements
- Integrate the MHD power system and its subsystems with the space platform and weapon system
- Quantify operating characteristics, requirements for operating modes, and interactions with the space platform
- Coordinate/produce technical documentation and deliverables
- Evaluate results of tests and experiments at the overall system level, and coordinate evaluations of tests and experiments performed at the subsystem level
- Identify and implement design changes and produce the Phase 1 Final Conceptual Design Description

RATIONALE FOR SELECTION

- Currently Advisory Engineer with responsibility for the definition and development of advanced power system concepts
- Managed technical direction of several recent, fast-paced studies of advanced power sources for military and SDI applications
- Previous MHD experience ranges from DOE/PETC Advanced Power Train Studies to early Westinghouse R&D MHD experiments in the 1960s
- Directed the multicontractor test train and facility system safety analysis for the DOE/MHD CDIF in Butte, Montana
- Originated conceptual designs of the Resistive Load Bank and the MHD channel electrical interfacing systems that were manufactured and installed at CDIF
- Has extensive prior experience in comparative evaluation of alternate power systems and integrated technical/economic tradeoff studies of space, military and commercial power systems
- Has more than 28 years of experience with B.S. and M.S. Degrees in Mechanical Engineering

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 4)

KEY PERSON - JOSEPH S. BRINDZA - FACILITIES AND TEST OPERATIONS
Westinghouse Advanced Energy Systems Division

RESPONSIBILITIES:

- Evaluate test facilities and specify requirements for test facility modifications and support equipment
- Prepare experimental procedures and plans with test article descriptions, process, instrumentation, and consumable requirements, safety requirements, operating requirements, and schedules
- Implement experimental plans in cooperation with other team members
- Oversee test operations to insure compliance with plans and procedures
- Provide notification of significant deviations and changes required in the DOE approved experimental plan

RATIONALE FOR SELECTION

- Currently Manager of Test Operations and AESD's Fuel Cell Test Facility with responsibility for administration, test planning and scheduling, test performance, training, maintenance, and facility modifications
- Responsible for AESD Fuel Cell Test Facility design, checkout, and initial testing.
- Previous MHD experience with responsibilities for electrical, instrumentation, and controls design for Westinghouse designed test support equipment installed at the DOE MHD Component Development and Integration Facility
- Test engineering experience with high voltage switchgear
- Experimental design and test experience with nuclear navy equipment
- B.S. in Electrical Engineering, 16 years of professional and mangement experience

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 5)

KEY PERSON - S. W. SILVERMAN - SPACE PLATFORM/WEAPON SYSTEM INTEGRATION
(Boeing Aerospace Company)

RESPONSIBILITIES:

- Assist in the integration of the MHD power system with the space platform and weapon system
- Define interface parameters based on SDI requirements, the space environment, and launch vehicle constraints
- Define and quantify interactive effects between the MHD power system, the weapon system, and the space platform; assess impacts due to MHD power system operation
- Provide weapon system and space platform data for MHD power system conceptual design
- Assist in revising the MHD power system conceptual design, as the result of analyses, experiments or tests

RATIONALE FOR SELECTION

- Extensive experience in airborne and spacecraft high voltage, power systems, and system engineering
- Manager of many previous electrical power system R&D contracts funded by NASA and the USAF
- Present position is Engineering Manager/Chief Scientist in the Electrical Power Systems organization of Boeing Aerospace Company
- Involved in Strategic Defense Initiative studies
- Member of NASA advisory committee on electrical power
- More than 30 years of experience with the Boeing Company
- B.S., Electrical Engineering, College of the City of New York and M.S., Electrical Engineering, University of Michigan

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 6)

KEY PERSON - J. L. KELLY - COMPONENT DESIGN AND FABRICATION
Westinghouse Advanced Energy Systems Division

RESPONSIBILITIES:

- Prepare the 100 MW_e/500 second power system and major component structural design, packaging, and layout drawings and provide the basis for weight, size, and cost algorithms
- Support Auxiliary Component design and engineering development activities and contribute to the resolution of key technical issues
- Design and fabricate major experimental hardware items via the following:
  - preparation of design and procurement specifications
  - vendor evaluation and selection
  - quality assurance procedures
  - cost and schedule control
  - acceptance testing
  - preparation of as-built design descriptions
- Coordinate internal Westinghouse design reviews and support DOE critical design reviews
- Provide input to experimental procedures
- Conduct post-test evaluation of experimental hardware items

RATIONALE FOR SELECTION

- Currently Manager of Equipment Design for Westinghouse AESD
- Major engineering task experience during the last five years includes: management of detailed mechanical and electrical design; manufacturing, procurement, and assembly support; equipment erection; and field support for developmental and first of a kind hardware for advanced energy systems.
- Prior related experience in the design of magnetic field coils and structures, dewars, shields, vacuum vessels, and neutron beam systems in fusion power programs
- Design, development, procurement, test and installation experience with naval nuclear hardware
- B.S. in Mechanical Engineering, graduate work in Electrical Engineering, 30 years of management and professional experience, registered Professional Engineer

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 7)

A. LEE CHILD - FACILITY AND TEST SUPPORT
Mountain States Energy, Incorporated

RESPONSIBILITIES:

- Assist in the preparation of the Task 2 Experimental Plan
- In response to test specifications, prepare designs for facility modifications and additions, develop implementation plans and schedules, and prepare cost estimates
- Implement facility modification/addition plan
- Install MHD test articles and perform facility/test article checkouts
- Conduct test operations in accordance with test plans and specifications
- Provide post-test operation summaries and engineering data tapes for analyses

RATIONALE FOR SELECTION

- Over 29 years of experience in engineering test activities with 21 years of experience in supervision/management of engineering and technical support personnel
- Extensive experience in instrumentation, laboratory and test operations, and quality assurance provisions for test programs and materials evaluations
- Presently Manager, Engineering Test Support Branch at the DOE/MHD CDIF for MSE, member of the MSE staff at CDIF since 1980
- Registered Professional Engineer (California) and member of National Society of Professional Engineers

Figure 5-17. Personnel Responsibilities and Qualifications (Sheet 8)

R. L. AMMON

Westinghouse Advanced Energy Systems Division

Technical Area: Materials

Qualifications:

- Has prime responsibility for refractory metal development programs
- Major contributions to the refractory metal field include development of three tantalum alloys, niobium alloys and process development for W-HfC wires
- B.S., Metallurgical Engineering, University of Arizona, M.S., Metallurgical Engineering, University of Arizona

F. E. BERNARD

Westinghouse Advanced Energy Systems Division

Technical Area: System Analysis/Computer Code Development

Qualifications:

- Development and modification of Westinghouse proprietary computer codes for system simulation and economic analysis
- Computer System Analysis and cost estimating for DOE MHD Advanced Power Train program
- Responsible for programming, operations, and maintenance of the AESD Hybrid Computer Facility
- Software programming and Hybrid Computer simulations of fuel cell power plants, wind turbines, and other advanced energy systems
- Thermal and Structural Analysis using Westinghouse and vendor computer codes
- B.S. in Applied Mathematics

A. BOLTAX
Westinghouse Advanced Energy Systems Division

Technical Area: Nuclear Fuel Technology

Qualifications:

- Managed NERVA fuel development at Westinghouse (1960-1967); work included development of advanced long life NERVA fuel, transient irradiation tests in the TREAT (Transient Experimental Test) Reactor and post-irradiation examination of fuel behavior in the NERVA reactor tests
- Managed breeder reactor fuel development involving oxide and carbide fuels
- B.S. and PhD., Physical Metallurgy, Massachusetts Institute of Technology

R. W. BUCKMAN, JR.
Westinghouse Advanced Energy Systems Division

Technical Area: Materials

Qualifications:

- Currently Manager of Materials Technology department responsible for providing support in the area of materials and process selection, development and evaluation of AESD advanced/alternate energy production concepts
- Principal investigator of refractory metal alloys for high temperature applications in advanced high temperature space and terrestrial reactor power systems; process development of columbium, tantalum alloy tubing, and chromium alloys
- B.S., in Metallurgical Engineering, University of Cincinnati, more than 30 years of experience

J. J. DUANE
Westinghouse Advanced Energy Systems Division

Technical Area: Project Control & Scheduling

Qualifications:

- Twenty-two years of experience in engineering and planning functions with Westinghouse
- Responsible for program planning and control for MHD programs, fuel cell, photovoltaic, and manufacturing projects at the Advanced Energy Systems Division
- Program management functions include scheduling budgets, work breakdown structures, reporting, purchasing logistics, data management, cost control, and performance measurement
- B.S., Mechanical Engineering, University of Pittsburgh, B.S., Management Systems, Carnegie-Mellon University

L. L. FRANCE
Westinghouse Advanced Energy Systems Division

Technical Area: Materials

Qualifications:

- Responsible for the NERVA reactor structural and insulating graphite technology, including structural and pyrolytic graphite selection, and mechanical, physical, corrosion and coating evaluations
- Responsible for the selection of materials, vendor materials related problems, and environmental effects for most plant components of the Fast Flux Test Facility and the Clinch River Breeder Reactor
- B.E., Mechanical Engineering, John Hopkins University, M.S., Metallurgical Engineering, John Hopkins University

J. P. HANSON
Westinghouse Advanced Energy Systems Division

Technical Area: System Analysis

Qualifications:

- MHD Test Article/Facility system modeling, simulation, and control system design for the DOE/MHD CDIF
- Design and analysis of radiators and heat transfer equipment for space power systems
- NERVA nuclear rocket engine system modeling and simulation studies
- Evaluation of MHD effects in fusion power plant cooling systems
- Ph.D., Mechanical Engineering, University of Pennsylvania, 25 years of experience

L. R. HEDGECOCK
Westinghouse Advanced Energy Systems Division

Technical Area: Radiation Shielding

Qualifications:

- Responsible for Clinch River Breeder Reactor radiation protection program; interfacing with project architect engineer and reactor manufacturing on all matters related to radiation source terms
- Responsible for the technical direction of engineers engaged in the design and testing of radiation shields for approximately 100 Naval Reactor plant shields
- M.A., Chemistry, Columbia University, B.S., Chemical Engineering, Michigan State University

E. L. KOCHKA
Westinghouse Advanced Energy Systems Division

Technical Area: Materials

Qualifications:

- MHD materials testing and channel design and fabrication
- Development and production of graphite based nuclear fuel elements for the NERVA program
- Development of vapor deposition process for carbides and other refractory materials
- B.S., Chemistry, Columbia University, M.S., Metallurgical and Materials Engineering, University of Pittsburgh

P. MARSTON
Massachusetts Institute of Technology

Technical Area: Magnet Design & Analysis

Qualifications:

- Thirty years total experience, 20 years of experience in MHD
- Currently head of MHD and high energy physics group at MIT Plasma Fusion Center
- Performing conductor development for MHD under DOE/PETC
- B.S., Marine and Electrical Engineering, Massachusetts Maritime Academy

H. O. MUENCHOW
Westinghouse Advanced Energy Systems Division

Technical Area: Engineering Design and Fabrication

Qualifications:

- Designed, analyzed and tested compact, high performance heat exchangers for the Aircraft Nuclear Propulsion Program

- Designed remote operating systems and components for Fast Breeder Reactor fuel handling, refueling and fuel storage

- Managed design and component testing of steam generators

- Managed engineering section for Liquid Metal Fast Breeder Reactor plant design

- B.S., Chemical Engineering, Michigan State University; 35 years experience

A. S. NAKAMURA
Westinghouse Advanced Energy Systems Division

Technical Area: System Engineering & Analysis

Qualifications:

- Principal Investigator for evaluations of alternate power sources for a space-based SDI weapons system. Developed size and mass algorithms

- Conceptual design and performance analysis of MHD and combined cycle power plants

- Process design and retrofits to present production and testing facilities

- B.S., Chemical Engineering, Washington University, five years experience

C. A. PORTER
Westinghouse Advanced Energy Systems Division

Technical Area: Nuclear Analysis

Qualifications:

- Development of concept reactor systems for both terrestrial and space based applications
- Nuclear design and analysis of advanced reactors ranging from light weight nuclear propulsion projects to large scale breeder reactor projects
- Overall responsibility for nuclear analysis computer code development and maintenance at AESD
- B.S., Physics, Carnegie-Mellon University

previously the Manager of Emerging Technologies at Westinghouse AESD where he was responsible for MHD and other advanced energy programs. He now holds a senior project management position at the Westinghouse R&D Center. His extensive experience in MHD, gas-cooled reactor technology and large scale development programs will be a valuable asset to the planned program. Dr. W. D. Jackson and Mr. G. S. Seikel have extensive experience in NASA and DOE programs. They have both made significant contributions to DOE-funded MHD programs performed by Westinghouse. Qualifications for each of the four Senior Technical Review Board members are provided on the following pages.

L. E. Van Bibber
Westinghouse Advanced Energy Systems Division
Senior Technical Review Board

Mr. Van Bibber is Manager of Emerging Systems at AESD. He has project management responsibilities for DOE/PETC clean coal technology and terrestrial MHD contracts. The MHD contracts he is responsible for include MHD retrofit utility plant design, power conditioning, and seed recovery and regeneration.

Mr. Van Bibber's previous engineering and management experience includes assignments as Manager of Systems Design and Integration and Manager of Wind Turbine Engineering. He has extensive experience in hydraulic, thermal, and systems analysis and in the development, design, installation, and field support for first-of-a-kind advanced energy systems.

A. R. JONES

Westinghouse R&D Center

Senior Technical Review Board

Mr. Jones preceded Mr. Van Bibber as Manager, Emerging Systems, at AESD. He was responsible for project management of MHD projects, hydrogen production development and DC power conditioning. Mr. Jones was the Project Manager for the Advanced Power Train project, performed for DOE/PETC. This major MHD project included the conceptual designs of MHD power plants ranging from 200 to 1000 MW_e. A major deliverable item was the detailed definition of the long range R&D Plan needed for MHD to be ready for commercial status.

Previously, Mr. Jones has served as Manager, Engineering, supervising and coordinating the efforts of Analysis, Materials, Design and Integration, and Drafting and as Manager, Special Projects.

W. D. JACKSON

President, HMJ Corporation

Senior Technical Review Board

Dr. Jackson is internationally recognized for his contributions to MHD. His speciality in the field of MHD power generation is the treatment of MHD generators as electrical machines and the development of appropriate power conditioning. He has recently been a member of the Westinghouse Team for the MHD Advanced Power Train.

Dr. Jackson's experience has been derived from positions in the Federal Government, industry and academia. From 1974 to 1979, he served in various capacities in the DOE and its predecessor agencies, including four years as Director of the Division of MHD. Prior to this he had been Manager, Thermal Mechanical Energy Conversion and Storage Programs, Electric Power Research Institute, Palo Alto, California and from 1967 to 1972 served as Principal Research Scientist at the AVCO-Everett Research Laboratory, Everett, MA in the MHD Group.

G. R. SEIKEL

President, Seitec, Inc.

Senior Technical Review Board

In his 25 years at Lewis Research Center (LeRC) with NASA and its predecessor, NACA, Mr. Seikel served in a variety of management functions related to MHD research.

As NASA's Manager MHD Systems/Manager MHD Project Office, Mr. Seikel negotiated and managed interagency agreements making NASA LeRC a major field center for the DOE MHD program with responsibility for defining plants and developing the key plant technology - the MHD power train. His contributions included studies which resulted in redirecting the DOE program toward plants using oxygen enrichment.

Prior to 1978, Mr. Seikel served as Chief of the Plasma Physics Branch for 12 years where he managed NASA exploratory research and technology on various advanced propulsion and power technologies: plasma thrusters, MHD, fusion, thermionics, heat pipes, and plasma lasers. He initiated NASA's MHD open-cycle and Department of Energy (DOE) reinbursed studies, directed the MHD portion of the definitive Energy Conversions Alternatives Study (ECAS), and directed the initial definitive technology for magnetoplasmadynamic (MPD) thrusters.

5.2.5 Matrix Organization and Procedures

Westinghouse AESD is organized in a matrix form because we have found this organizational structure to be best suited to the performance of high technology programs that require a changing mix of personnel with specialized skills. A strong project management organization, the engineering department, and other functional organizations, are used to concentrate resources on the achievement of program objectives. Once assigned to a specific program, each project manager has complete authority to command the required resources and to manage the program within the terms and conditions of the contract. The project manager is always the single point of contact between the customer project manager and Westinghouse. He is responsible for planning and executing all of the work effort and for periodic internal reviews before Division and Business Unit management.

The project manager has access to the engineering department personnel with the specialized skills necessary for a given statement of work.

Once assigned to a program, personnel within the Engineering Department are responsible for the performance of specific tasks identified in the Work Breakdown Structure and report progress and status directly to the project manager. The line managers within the Engineering Department are responsible for ensuring high standards in the performance of the work and in the reporting of the results. Engineering line managers also are responsible for screening personnel for assignments, measuring the performance of assigned personnel, improving personnel productivity, and ensuring their continuing professional development. On a regular basis, the engineering line managers review the performance of assigned personnel with project managers as part of the Westinghouse Performance Management System.

The AESD project managers also utilize techniques and practices that have been proven and refined on projects ranging in scope from small specialized materials testing projects to the design of liquid metal fast breeder reactor plants. The project planning and control procedures that are used for the MHD Feasibility Assessment Program follow these established procedures for planning, managing, and controlling technical workscopes. The Westinghouse Integrated Management and Control System (IMACS) was designed to provide overall project control by authorizing/delegating workscope and responsibility, and by tracking the associated funding through the various phases of a given contract. IMACS has been utilized successfully on projects of varying size and complexity. Budgeting, cost accumulation and variance determination, and manpower support projections are used by project management to monitor, control and report project costs and to assure that manpower resources are utilized effectively and efficiently. The Westinghouse Work Authorization System serves as the vehicle to initiate, interface, and authorize work to be performed to meet the requirements and obligations of a Customer Order. The computerized Action Commitment Expediting System (ACES) is utilized for commitment and schedule control. ACES supplements IMACS by tracking specific contract commitments, reportable contract milestones and internal nonreportable planning milestones. These systems are currently in place and ensure that accurate and timely fiscal and schedular information are provided to DOE in the most efficient and cost effective manner.

5.3 TASK 2 RESEARCH AND DEVELOPMENT PLAN COSTS

Budgetary estimates for Task 2 have been made considering three different facility options for the experimental hydrogen driven disk generator (WBS 1250). The budgetary estimate for Option 1, which utilizes CDIF with power supplied to the arc heater power supplies at 4800V, is $6.7 million. By reducing the input arc heater power supply voltage to 4160V at CDIF and thus input power (reduced by ~ 15%), the budgetary cost estimate for Task 2 is $5.9 million. The lowest budgetary cost estimate for Task 2 ($4.8 million) is obtained by using the Westinghouse Plasma Center where four 5 MW power supplies are installed. Due to the significant cost difference, a task has been added early in Task 2 (WBS 1250) to assess facility capabilities in more detail and conduct a more detailed review of the costs. This will be completed and a facility recommendation will be presented by the third month into the Task 2 program.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The work carried out during Task 1 has confirmed that the Space-Based Multimegawatt MHD Power System is a highly promising concept. The technical questions remaining can be clarified and resolved through reasonable extension of existing theoretical knowledge and experimental investigation.

The advanced development of the nuclear heat source for orbital/space operation, coupled with the disk MHD generator offers the promise of an effective power source for orbital SDI missions. The system has the inherent potential to deliver the rapid power bursts required for the defined missions. The system also has a volume envelop that will permit its delivery into orbit by either manned or unmanned launch vehicle presently existing, and a low combined system mass.

Work already completed, including test operations of similar nuclear reactors as well as on going reactor development/refinement for other programs, limits the need for work in this area during Task 2 of this program. Thus, the major part of the Task 2 effort will focus on experiments to confirm stable operation at the desired system parameters for the disk MHD generator and plasma.

It is recommended that during Task 2, a priority program of investigation be carried out employing an existing laboratory MHD generator to expand and refine knowledge of plasma parameters and disk MHD response in the range of conditions that apply for the Space-Based Multimegawatt Power System. The Task 2 plan is described in the Research and Development plan, Section 5 of the report.

In addition, further effort to define the Power System requirements and guidelines for design will be performed. This work will encompass further study and investigation of the individual subsystems and refinement of the performance requirements for each. Further study of questions including launch and orbital assembly and commissioning, hydrogen handling and delivery, and effluent control are also recommended.

Task 2 will require approximately 2 years to complete at a cost in the order of $5 million. Successful resolution of key technical issues in Task 2 will confirm the viability of the system as a superior solution for the SDI mission.

Major conclusions of Task 1 include:

- The proposed nuclear disk MHD generator system is a viable approach for which mass and performance has been basically affirmed.

- A viable test program can be mounted to resolve the three key technology issues of hydrogen plasma properties, energy extraction and endurance capability.

- Confirmation of hydrogen properties with the nitrogen analog.

- Extraction and nonequilibrium plasma were verified at high Hall parameter values in TIT blowdown facility.

- SPA system and MHD disk model were validated with TIT data.

- Lower seed fraction (5×10^{-5} vs. 1.5×10^{-4}) than proposed.

- MIT disk MHD generator can adequately resolve plasma property questions and determine plasma properties.

- Alternatives to copper coil have been proposed; a LH_2 cooled aluminum hyperconducting coil is much lighter.

- A separate magnet electrical system and control are preferred.

- An alternate test site for the endurance experiment has been developed that would potentially reduce the cost of this experiment significantly.

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15. ABSTRACT--PURPOSE, SCOPE, APPROACH, RESULTS, CONCLUSIONS, SIGNIFICANCE: (MAXIMUM: 200 WORDS)

This Topical Report presents the results of Task 1 of the Feasibility Assessment for Space-Based Multimegawatt MHD Power Systems program and consists of two volumes. Volume I contains the System Design, Key Technical Issues, R&D Plan and Recommendations. Volume II contains the System Requirements, Design Guidelines and Assumptions for the MHD power system. Supplemental information, including cost estimates, is in WAESD-TR-88-0004.

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